ELECTRICAL ENGINEERING

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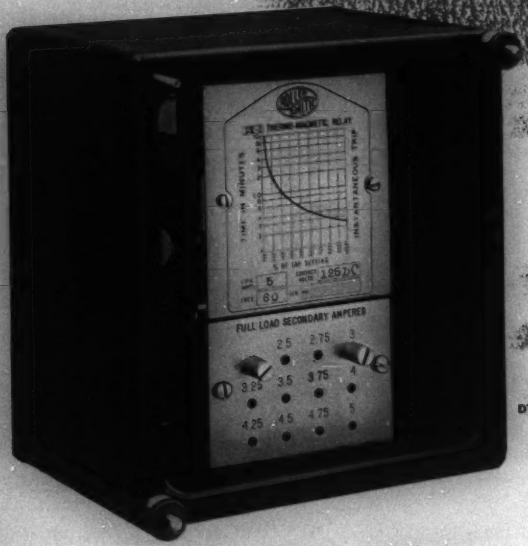

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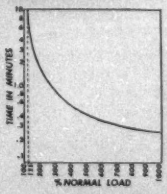

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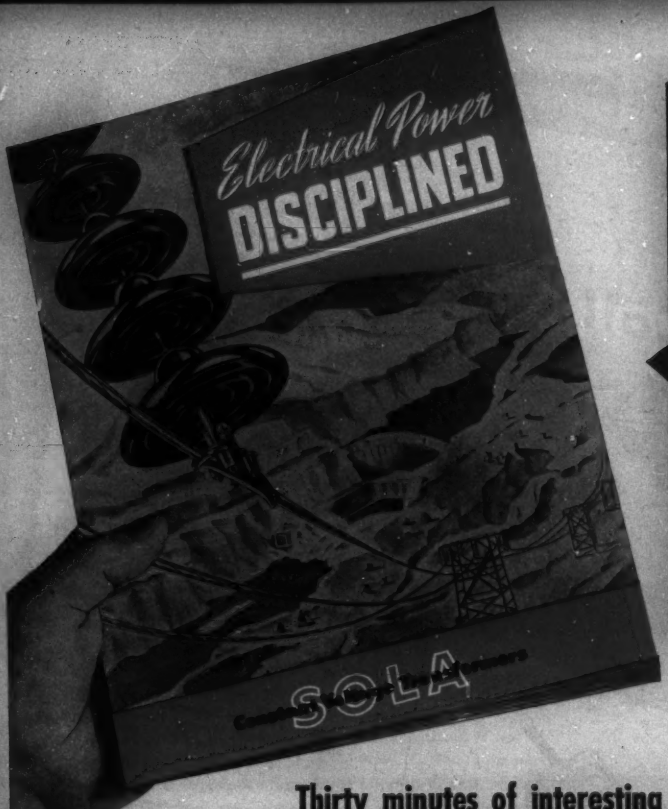

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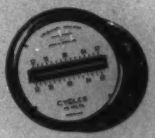

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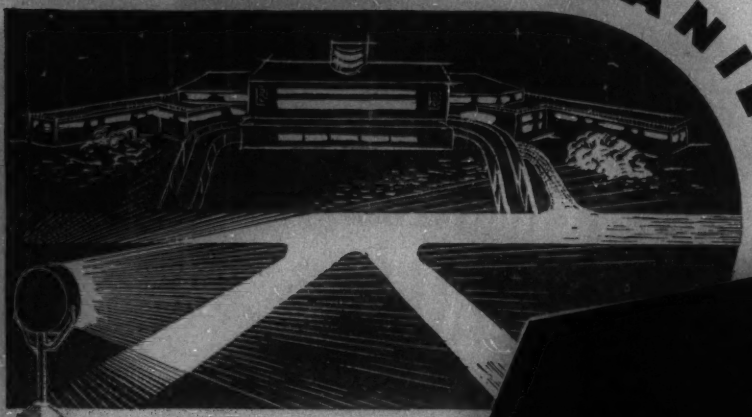

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Some Experiences With the X Ray.....W. D. Coolidge . . . 423
X-Ray History and Development.....W. D. Coolidge, E. E. Charlton . . . 427
Industrial X-Ray Developments.....C. D. Moriarty . . . 433
X Rays an Early Institute Topic . . . 435
Scientific Importance of X Rays.....L. Henry Garland . . . 437
50 Years of X-Ray Progress in Europe . . . 444
Statistical Methods in Quality Control—VII.....AIEE Subcommittee . . . 448
Miscellaneous Short Items:
X Ray in Industrial Inspection, 426
Betatron for 100,000,000-Volt X Rays, 450
Institute Activities . . . 451
Of Current Interest . . . 461

TRANSACTIONS SECTION

(Follows EE page 470; a preprint of pages 807–72 of the 1945 volume. Any discussion of these papers will appear in the December 1945 "Supplement to Electrical Engineering—Transactions Section" and in the 1945 volume.)

Resonant-Circuit Constant-Current Regulators.....G. M. Kevern . . . 807
Parallel Operation of 400-Cycle Aircraft Generators.....L. G. Levoy, Jr. . . . 811
Electric Power in a Steel Plant.....R. W. Graham . . . 816
Maintenance of Good Brush Performance.....W. C. Kalb . . . 819
Carrier-Current Relaying.....A. J. McConnell, T. A. Cramer, H. T. Seeley . . . 825
Resistivity of Wood and Plastics.....Richard C. Weatherwax, Alfred J. Stamm . . . 833
Per-Unit Impedances of Synchronous Machines—II.....A. W. Rankin . . . 839
Quality Control of Motor Windings and Cores.....P. H. Trickey . . . 842
Power Systems for Auxiliary Drives.....J. B. McClure, S. I. Whittlesey . . . 844
Study of Costs of Power-Transmission Systems.....John G. Holm . . . 852
Equivalent Circuits of the Synchronous Machine.....A. W. Rankin . . . 861
Modern Practice in Power-Plant Auxiliary Equipment.....H. N. Muller, Jr . . . 868

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ELECTRICAL ENGINEERING

VOLUME 64, NUMBER 12 DECEMBER 1945

Some Experiences With the X Ray

W. D. COOLIDGE
MEMBER AIEE

November 1945 commemorates the 50th anniversary of the discovery of the penetrating power of the X ray by William Conrad Roentgen. Here another pioneer discusses some of his early experiences with the tube, its gradual evolution, and its current importance.

THE 50-YEAR PERIOD which this month brings to a close began during my senior year as an electrical-engineering student at the Massachusetts Institute of Technology. That year marked the announcement of Roentgen's discovery of the X ray which soon was followed by intensive work by several members of the teaching staff at the institute on various forms of high-voltage generators to operate the tube. This work was done in collaboration with Doctor Francis Williams of Boston, one of the earliest pioneers in the application of X rays in the medical field, and it was my exciting privilege to witness many of these developments.

In addition to this I spent many evenings with a friend who had a large static machine from which various X-ray tubes were operated. Later I built a static machine of my own for the same purpose.

I became acquainted very early with the destructive effect of X rays upon living tissue. In fact it was only a few months after the announcement of Roentgen's discovery that I required medical care for an X-ray burn covering most of the back of one hand.

MEETING WITH ROENTGEN

In 1898, while a student in the University of Leipsic, Germany, I was greatly thrilled one day when Professor Roentgen entered the room in which I was working on my thesis. Geheimrath Gustav Wiedemann had died recently and Roentgen had been called in to take his place as head of the physics department. The impression which I received was an unforgettable one. It was heightened by the fact that I had previously pictured Roentgen as a frail and sickly looking individual rather than as the robust person before me who was so tall that he could just enter the door without stooping.

The new physics institute in Leipsic had just been completed and the living quarters of the Roentgens would have been on the top floor. However the front windows overlooked the cemetery and I heard that this view proved unacceptable to Mrs. Roentgen. Be that as it may, the call to Leipsic was not accepted.

ROENTGEN TUBE AS VACUUM FURNACE

In 1905, when I left Massachusetts Institute of Technology and joined the staff of the research laboratory of the General Electric Company in Schenectady, N. Y., I found there an urgent need for a vacuum furnace for melting refractory metals, including tungsten, which were being studied in the hope of finding something better than carbon for the filament of the incandescent lamp. My early experience with X-ray tubes naturally suggested that any material placed at the focus of the cathode rays in such a tube either could be melted or vaporized and, because of the vacuum, without contamination from the atmosphere. With this in mind I returned to the institute and for several weeks, with the help of a large Heinz induction coil and other equipment kindly lent me by the physics department, I had the experience of working on the development of X-ray tubes in which, for the first time perhaps, one wanted the targets to melt. For these experiments I did not get beyond the stage of using graphite targets. This was perhaps fortunate for me as graphite, with its low atomic number, is a very inefficient source of X rays and I was using much energy in the tubes and did not have adequate means of protection. In fact, when Doctor Williams visited me in order to acquaint himself with the X-ray output of one of the tubes, he said, upon leaving, that in all his experience he had never before been so much exposed to the rays.

TUNGSTEN-TARGET DEVELOPMENT

In Schenectady, when, after several years' work on tungsten, we had succeeded in making that originally brittle metal ductile and had learned how to make good lamp filaments from it, we looked for other applications. One of the first of these was as a substitute for platinum in the target of the X-ray tube.

Experiments were needed not only to determine design features but also to learn the best metallurgical characteristics of the tungsten metal for the target face. To facilitate the experiments the most powerful X-ray generator of that time, a 10-kw Snook transformer machine, was acquired. As the purpose of the study was the development of as robust a target as possible, the experiments involved serious overloading of the tubes. This overloading developed weaknesses in this type of tube which manifested themselves in the form of punctures in the glass envelopes and in cracks due to local overheating. These troubles subsequently were reduced by operating the tubes immersed in oil but new limitations then presented themselves. With the heavier loads which could be used with oil immersion the aluminum cathodes melted. In addition there was the ever-present difficulty of controlling the gas pressure in the tubes.

THE HOT-CATHODE HIGH-VACUUM TUBE

To avoid the melting of the aluminum cathodes, we tried replacing them with tungsten. This resulted in a tube which was hopelessly unstable ("cranky" in the language of the time).

In another tube the target and cathode both were made of massive tungsten and were identical in form. This tube also was very unstable. The cathode showed essentially the same heating as the target, and the positive ions which bombarded it were about as sharply focused as were the electrons striking the target. It was at first impossible to operate it for more than an instant at a time as, with the application of high voltage, the gas immediately would clean up. It later developed, however, that if the gas pressure then were increased quickly by means of the regulator, the tube again could be operated for an instant, and that if this procedure were repeated several times in quick succession the cathode would become very hot and, in this condition, the tube could be operated continuously. This seemed to

An article prepared for the *American Journal of Roentgenology and Radium Therapy*, December 1945, volume 54, and published in *Electrical Engineering* in collaboration with that publication in joint recognition of Roentgen's contribution to science.

W. D. Coolidge is X-ray consultant, Research Laboratory, General Electric Company, Schenectady, N. Y.

bespeak interesting possibilities for a tube in which the cathode could readily be heated at will. The idea of getting electrons from a hot body was not new. Thomas Edison had observed it in the incandescent lamp and O. W. Richardson had investigated the relation between electron emission and temperature. There was, however, much skepticism among physicists at the time as to whether electron emission would continue in case the gas were completely removed from the hot body.

At just the time, however, when we had become conscious of the fact that most of the limitations of the original type of Roentgen tube were due to the gas content, without which it could not operate, and were wishing for a stable source of electrons in a high vacuum, Doctor Irving Langmuir, of our laboratory, was studying electron emission from hot tungsten filaments. He found that even in the highest vacuum the emission was stable and reproducible and that it was even favored in amount by freeing the cathode filament of its original gas content.

These circumstances led me to the construction of experimental high-vacuum tubes with a heated tungsten filament as cathode and a tungsten disk as anode. Until these tubes had been continuously pumped for many hours by an exhaust system which was good at the time, but which now would be considered very slow, they showed some of the green fluorescence of the glass which always had attended the operation of a Roentgen tube. However, as the electrodes became freed of gas, this fluorescence became less and finally disappeared completely. The tube was then stable and controllable, and we were able to satisfy ourselves that its behavior was the same as it would be even if it had a perfect vacuum. The positive ions, essential to the operation of the earlier tubes, were no longer needed and the limitations, most of which were due to the presence of those positive ions, were gone with them.

Doctor Lewis Gregory Cole in New York was the first roentgenologist to be equipped with the new type of tube. To introduce it and me to the medical profession, he gave a dinner in New York on December 27, 1913, to which he had invited many prominent roentgenologists. A powerful high-voltage generator had been installed in the dining room by Doctor Harry Waite, of the firm of Waite and Bartlett, and with it I was privileged to demonstrate the new tube. Upon recalling the affair now, it seems surprising that the audience stayed through the demonstration. Up until that time the capacity of high-voltage X-ray generators had been considerably in excess of what the tubes could stand for any length of time, but with one of the new tubes having a sufficiently large focal spot this was no longer true. I opened the machine up wide and, with the limited amount of protection which the open lead-glass bowl of that time afforded, the audience must have received many more X rays than they were accustomed to experience.

Doctors Cole, James Case, Walter Dodd, Eugene Caldwell, George Pfahler, Preston M. Hickey, and many other roentgenologists were very helpful to us in those early days in adapting the new tube to the various medical applications.

MYSTERY OF ROENTGENOGRAPHY

The gas-filled X-ray tube had not been easy to control and its successful use had called for both patience and experience. It was probably as a result of the idiosyncrasies of that type of tube that it was not uncommon to hear an expert roentgenologist say that once upon a time he had made a wonderful roentgenograph whose quality he had never since been able to equal. There seemed to be some mystery connected with this—possibly some particular X-ray spectrum was most desirable.

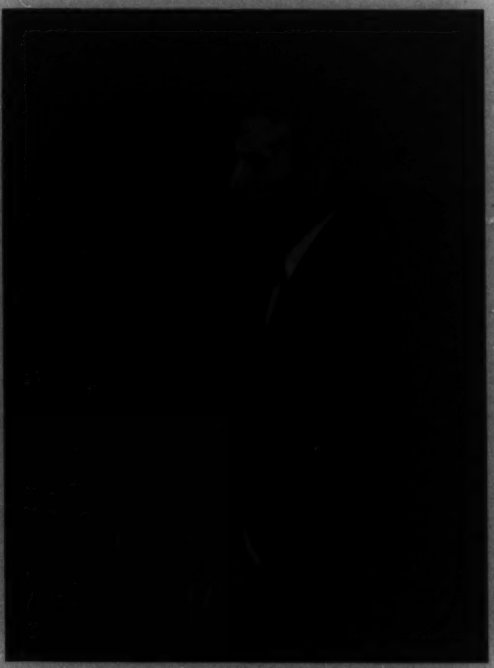
A factor which had contributed to the difficulty of clearing up the mystery was the runaway tendency of the discharge through the gas-filled tube. This had made it necessary that the high-voltage source employed should not have good regulation; that is, that for any given setting of the controls, its voltage should fall rapidly with the milliamperage drawn by the tube.

As a result, it had always been very difficult to know what voltage had been effective in producing a given roentgenograph. As ordinarily used, the parallel spark gap indicated the voltage required to initiate the discharge but this was usually quite different from, and appreciably higher than, the voltage across the tube when it was later carrying current and so producing X rays.

With the new stable tube, in which the starting and running voltages were the same, we found it desirable to use a high-voltage source which did not have a falling voltage characteristic but instead had good regulation. It was then possible to know in advance what both the milliamperage and the voltage were going to be.

Another factor which must have played some role in creating the mystery was the size of focal spot. In a gas tube this was not constant but could vary appreciably with the pressure even during an exposure. Not only this, but as the pressure changed, the position of the focal spot could change also.

There was at the time but little knowledge concerning the matter of focal-spot size. It was quite common for the manufacturer to receive an order for a tube with "pinpoint focus." Such a tube, had it been delivered, would of course have been unsatisfactory because of the energy limitation which this would have imposed. This limited knowledge concerning the size of focal spot was such a handicap in the art that for some time after beginning the sale of the hot-cathode tube we supplied with each



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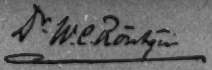

one a natural-size X-ray pinhole camera picture of its focal spot.

With the hot-cathode tube, in which current and voltage were under independent and accurate control, and the focal spot was of known and unvarying size and fixed location, we were in a position to attempt the solution of the mystery concerning that occasional outstanding roentgenograph that could not be duplicated. As a subject was needed for the experiment, I called on one of my medical friends for assistance. (I had temporarily and unintentionally sacrificed my own back hair to previous experiments and did not like to practice on other living subjects.) My friend provided me with material which was very useful over a period of months. I wish that I might make fitting acknowledgment at this time to the willing and complacent subject of those experiments. (I cannot think of it even today without smelling formaline.)

Later experiments with the detached leg of another passive subject led to a serious misunderstanding. As it happened, upon completion of these experiments, we wrapped the member in question in a fabric which was easily available to us, varnished cambric, and took it to the works' incinerator. The operator in charge removed the cover and we inserted the package, making no attempt at explanation, as the attendant did not understand English very well. It seems that, after we left, he raised the cover of the incinerator, and, looking into the furnace, saw our varnished cambric unwrap itself, revealing what seemed to be evidence of a ghastly crime. We later received a visit from our works' detective who was in a very serious mood. We explained and explained but have never been sure that he has ceased to regard us with suspicion.

The conclusion drawn from these experiments was that there was no mystery—that, other things being equal, contrast was determined solely by the voltage used and that definition was a function of the size and fixity of position of focal spot. We concluded that if one had his choice he would not use the mixture of rays which the tube gives, but would take monochromatic radiation of a wave length dependent on the thickness of the part to be radiographed; but that, not having this choice, he must be content with that mixture of rays coming from the tube when operated with the voltage which gives the desired contrast. Increasing the breadth of the spectrum used, by making a part of the exposure with low voltage and the rest with high, did not help.

FIELD CURRENTS

It appeared early in the course of our work that if cathode and target were brought very close together, or if there were a sharp point on the cathode, a high-voltage discharge could take place even from a cold cathode and in the highest attainable vacuum.

In poorer vacua a similar effect had been observed and described by H. A. Rowland, N. R. Carmichael, and L. J. Briggs, and by R. W. Wood.

Upon learning that electrons could be pulled out of a cold cathode, even in the highest vacuum, by means of a high potential gradient, the question arose as to whether a tube based upon this principle might not, because of the greater simplicity involved in the control equipment, be more attractive than a hot-cathode tube.

Extensive efforts which we made at the time, however, as well as all subsequent experience, have borne out the conclusion then reached that such a discharge is not sufficiently stable. Nor does it offer the great flexibility of the hot-cathode tube which permits independent control of milliamperage and kilovoltage.

Not only did we decide not to make use of field currents but it soon developed that we must take steps to avoid them, as they otherwise set a limit to the voltage which a tube could support. For operation at high voltage we found it helpful to avoid sharp edges and corners on the electrodes and to space them well apart. Even with these and other precautions, however, it proved difficult to get above a few hundred thousand volts until we hit upon the expedient of grading the potential by means of auxiliary electrodes. The resulting cascade tube made it possible to avoid field-current limitations and so to build tubes for any desired voltage.

THE RADIATOR TUBE

World War I brought interesting experiences in connection with the development of X-ray equipment. For use near the front it was clearly desirable to have a simple self-contained and dependable generating outfit of adequate power and maximum portability. It was obviously desirable to eliminate, if possible, the mechanical high-voltage rectifying switch which was in general use at the time. This was before the days of the kenotron but was still possible if we could develop a hot-cathode Roentgen tube which could be depended upon to rectify its own current. To meet this requirement it was imperative that no part of the focal spot ever should reach the temperature at which appreciable thermionic emission would take place. This would lead to electron bombardment of the cathode filament thus raising its temperature and causing runaway with consequent destruction of the tube. One factor was very favorable; the amount of available energy was going to be definitely limited by the capacity of the gasoline-electric generator. The "universal" tube with its solid tungsten target would have been safe for occasional use, starting with a cold target, but not for the very frequent use which war service required. These considerations led to the development of the "radiator" tube with its composite target, heavy copper stem, and external radiator for rapid heat removal. The target itself was that which had been developed earlier for the gas tube but much experimentation was required before we were able to free the large mass of copper sufficiently from gas. For X-ray protection, a heavy two-piece lead-glass shield was developed to surround the tube completely. This tube and shield served for both the United States Army portable and bedside outfits.

I knew of no lightweight gasoline-electric set suitable for the power supply of the portable outfit. It seemed possible that a motorcycle could be used to advantage as a highly portable power supply and belted to an electric generator at the point where X rays were required. Through the courtesy of the Indian Motorcycle Company I was provided with a motorcycle on which I took my first motorcycle ride. One experience was enough to satisfy me that this was not the way to treat the roentgenologist.

Through the application of tungsten contacts in the automobile-ignition system, I had become acquainted with Charles F. Kettering, then of the Delco Company, and this connection suggested the 1-kw house lighting set of that company. This was a lightweight 32-volt gas-engine-driven d-c generator. We needed an a-c generator and, for ready adaptation to a high-voltage transformer which we had found already in production by the Victor X-Ray Company, we required 115 volts. The Delco Company obligingly made changes required in the generator, but the engine did not respond well to having the full X-ray load thrown suddenly upon it. I found it necessary to ask for Doctor Kettering's personal assistance. He spent a whole week with us in Schenectady and so modified that engine that it was able to accept the suddenly applied load promptly.

Doctor John S. Shearer, then professor of physics at Cornell University, had assumed the responsibility for the design of the "portable" table and he co-operated closely with us in harmonizing table and X-ray source.

Shipment of the tube caused us much worry at first. Our experience was all in favor of a lightweight open-work crate which permitted the handler to see the glass, and so made him constantly aware of its fragility. But army shipping instructions called for a solid crate suspended from the corners of another solid crate and we were told that the tube so packed must stand dropping from a dray onto a stone pavement. We found that our tubes would stand this treatment but, in the first lot shipped abroad in this way, 40 per cent were broken. We then were permitted to use our fragile open-work crates and, when shipped in this way to the war zone, only one per cent were broken.

OIL-IMMERSED EQUIPMENT

The fact that the hot-cathode tube could be made very small, especially for oil im-

mersion, could rectify its own current, had a long life, and did not need to be seen during operation, made it seem very attractive to install it in the same metal container with the transformer serving as the source of high voltage. In this way it was easy to secure excellent X-ray protection, as well as protection from electric shock. Many small outfits of this type have been used for dental work and other purposes, while larger ones have been used for therapy.

In connection with our work on what might be called a glorified Lenard tube, we had tried to develop the induction coil for very high voltage. Using a mercury-turbine interrupter for the primary current, we had succeeded in attaining 900,000 volts. The difficulties, however, increased rapidly with voltage and it appeared very difficult to go much higher by this method.

In 1932, when I became director of the laboratory, Doctor E. E. Charlton was made head of our X-ray section and, ably assisted by W. F. Westendorp and others, still holds that position. Since then I have been able to devote much less time to this field, but have had the privilege of being a very interested observer.

THE RESONANCE TRANSFORMER

My earlier experience with the induction coil and other high-voltage sources has made me very appreciative of the low-frequency resonance transformer developed by Mr. Westendorp. This required no iron in the center, thus permitting the Roentgen tube to be placed there where it would be electrostatically shielded by the transformer and where the connections between tube and transformer would be very short and also completely shielded.

It has been very interesting to watch the development in Doctor Charlton's section of the 1,000,000- and 2,000,000-volt Roentgen outfits employing the resonance transformer and compressed-gas insulation. By this method it looks practicable to go still higher to perhaps 4,000,000 or 5,000,000 volts and with several milliamperes of current.

It also has been a pleasure and a privilege to watch the development of the betatron. After Doctor Kerst, working at the University of Illinois, had built a successful small machine which gave 2,300,000-volt X rays, he procured a leave of absence from the university and joined our research staff. He was with us for more than a year. During that time, with the help of Doctor Charlton's group, a larger machine embodying the same principles was designed and built. This operated satisfactorily at 20,000,000 volts. Since then we have built a still larger machine of the same type which gives X rays of any voltage from 2,000,000 or so up to 100,000,000. The fact that it has been possible to proceed so directly from Doctor Kerst's first machine to one giving over 40 times the voltage would augur well for future further advances in this direction.

SIGNIFICANCE OF ROENTGEN'S DISCOVERY

During the past 50 years the X rays indirectly have extended our vision greatly. Our eyes respond directly to a region of the spectrum which is only one octave in length. The rays were first produced by Roentgen at perhaps 25,000 volts. Through the years we gradually have worked up to a few million volts and now, with the betatron, to 100,000,000 volts. In the other direction we have gone down to as low as 1,000 volts. The X-ray spectrum available today then covers a range of more than 16 octaves and indirectly extends our vision to this extent.

The X rays have shown us the relation between the various chemical elements. They serve as a means of chemical analysis and they enable us to measure the distance between the atoms in a crystal and so to determine crystalline structure.

They also perform an invaluable service in medical diagnosis and are a powerful therapeutic agent.

The X rays occupy a rapidly expanding place in industry. They are used to show cavities and foreign inclusions in structural and other materials, to indicate whether vital internal parts of a structure are present and in proper position, and recently as a thickness gauge which does not require contact with the part to be measured.

The very-low-voltage X rays are used in microroentgenography as a means of studying the composition of very thin metallic specimens and to reveal structure in delicate botanical and zoological tissues. They may be used to produce genetic changes in plants and animals.

Lastly, and to the physicist most important, the X rays have, perhaps more than any other single agency, advanced our knowledge of the structure of matter.

At the close of these reminiscences I take the opportunity to acknowledge the help and the pleasure which I have derived from my close association through the years with the many doctors, dentists, physicists, industrialists, and others interested in the various uses of X rays.

X Ray in Industrial Inspection

X-ray equipment, manufactured by the North American Philips Company, Inc., used for radiography or fluoroscopy in the inspection of industrial parts for flaws. Operator is shown placing a trayful of small metal castings into specimen chamber. The lead-lined door then is closed, after which the unit may be energized. An eyepiece below the tray permits visual inspection. For radiography the film is placed under tray in chamber

X-Ray History and Development

W. D. COOLIDGE E. E. CHARLTON
MEMBER AIEE

Development of X-ray equipment from the early gas tube used 50 years ago by William Conrad Roentgen to the present-day induction electron accelerator is traced. Topics discussed include the various types of tubes involved in X-ray history, the limitations of each, and the attainment of an invaluable industrial and scientific tool.

SINCE its birth, the X-ray tube has undergone many radical changes. The general method of producing X rays is, however, still the same, namely by accelerating electrons to a high velocity and then suddenly stopping them by collision with a solid body, the so-called target.

Depending upon the method used in generating the electrons, Roentgen tubes may be classified into two general groups, gas tubes and high-vacuum tubes. In the first group, the electrons are freed from a cold cathode by positive ion bombardment, thus necessitating a certain gas pressure. In the second group, the vacuum is made as good as possible and the electrons are freed from the cathode either by heat, by bombardment by other electrons, or by the use of a potential gradient high enough to remove them electrostatically.

THE GAS TUBE

The first X-ray tube was of a form previously employed by Crookes in his experiments on electrical discharges through rarefied gas. The electrons liberated by positive ion bombardment from the flat aluminum cathode were emitted in a direction perpendicular to its surface and, under the impressed-voltage gradient, traveled in straight lines to the glass wall of the tube where they generated X rays.

This first X-ray source soon was greatly improved by Campbell-Swinton through the introduction of a platinum-foil target and by Professor H. Jackson through the substitution of a concave cathode for the original flat one. A later step of great importance was the addition of a device for regulating the vacuum. The early tubes were small and easily ruined as so little energy was necessary to melt the thin electrodes and to overheat portions of the glass envelope.

The power of the tubes was increased greatly by making them larger and with more massive cathodes and targets. The development of the target in particular received much attention. It resulted in a change from the use of a simple piece of sheet platinum to a platinum-faced disk of nickel brazed to a massive block of copper. This greatly increased the rate of heat flow away from the focal spot and also increased the heat-storage capacity.

A further substantial increase in tube power was obtained later by the development of a tungsten-faced copper target which consisted of a disk of wrought tungsten onto which a large mass of oxygen-free copper had been cast in a vacuum. The principal properties desired in the target facing are high atomic number for maximum X-ray efficiency, a high melting point, high thermal conductivity to allow maximum energies for a given size of focal spot, and a low vapor pressure to reduce the amount of target metal vaporized. Of all the chemical elements, tungsten combines these properties best.

The electrical characteristics of the gas tube were determined mainly by the gas pressure existing when the tube was carrying current. Owing to two opposing effects this pressure could be either higher or lower than it was before the tube was energized. Heat development resulting from positive ion and electron bombardment tended to liberate adsorbed gas from the glass and from the electrodes and so tended to raise the gas pressure. On the other hand, there was an electrical pumping action during operation which tended to reduce the pressure.

Even though the pressure might remain constant, the electrical discharge through the gas tube was of a runaway character. To combat this and to stabilize the discharge, it was necessary that the high-voltage source should have very poor regulation, that is, that its voltage should decrease rapidly as the current drawn by the tube increased.

If the pressure in the tube were too high, the voltage at all settings of the control would be too low. In the ordinary gas tube the only recourse then was to electrical cleanup. By operating the tube with current low enough to avoid appreciable heating, the gas pressure gradually would decrease. If the pressure were too low, it could be increased by admitting gas from the regulator.*

The initial pressure required for satisfactory operation was strongly dependent on the past history of the tube. The useful life was limited by the permanent electrical cleanup of gas and especially by the removal of adsorbed gas from the cathode. This last effect manifested itself by marked instability which finally became so bad that it was useless to add gas from the regulator as, on the application of high voltage, it would be immediately cleaned up. The tube then could be returned to its original condition only by rebuilding it with a fresh aluminum cathode, and it was necessary that this aluminum should contain hydrogen. It was apparently the gradual loss of this hydrogen from the cathode that was most responsible for instability. This was, at least in effect, recognized by the manufacturers of such tubes who carefully refrained from operating them any longer than necessary while connected to the pump.

As a result of the tube and circuit characteristics, it was difficult to know in advance what the voltage across the tube terminals during an exposure would be, and even difficult to know afterwards what the X-ray producing voltage had been. The tube voltage was measured by means of a spark gap connected in parallel with the tube but, as customarily used, this indicated the starting or breakdown voltage which was often much higher than the running voltage.

The size of focal spot was not constant but depended on the gap pressure and could vary appreciably even during an exposure. Not only this, but, as the pressure changed, the location of the focal spot could change also.

In the early hot-cathode tube of J. E. Lilienfeld[1] the main electrodes were the same as in the ordinary gas tube. By means of current flow between a pair of auxiliary electrodes, the cathode of which was heated, the gas of the tube was ionized. By varying the discharge current passing between the auxiliary electrodes, the conductivity between the main electrodes could be controlled. The tube operated with a gas pressure somewhat lower than that of the ordinary gas tube. It was still a gas tube, however, and was not operable if the pressure became too low.

THE HIGH-VACUUM TUBE

Most of the troubles experienced with gas X-ray tubes could be associated with the gas itself and the positive ion bombardment that took place when that gas was present. It was very desirable to get rid of the gas but this made it imperative to have some other mechanism for getting electrons out of the cathode.

An article prepared for *Radiology*, December 1945, and published in *Electrical Engineering* in collaboration with that publication in joint recognition of Roentgen's contribution to science.

W. D. Coolidge is X-ray consultant and E. E. Charlton is a research physicist, both with the General Electric Company, Schenectady, N. Y.

* This assumed various forms, often consisting of a side tube containing a chemical which upon being heated, as by the passage of a spark, gave off gas.

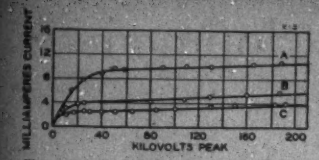

Figure 1. Curves showing the relation of current to voltage in the hot-cathode high-vacuum tube

Filament amperes: A—3.6; B—3.5; C—3.4

Edison, in his work on the incandescent lamp, had shown that in the vacuum of the lamp current could be made to flow from the hot filament to an anode. Much additional light had been shed on this phenomenon by the work of O. W. Richardson[3] and others. They connected electron emission with the temperature of the hot body. The general belief had come to be, however, that the whole hot-cathode effect resulted from gas contained in the cathode itself and that no current would flow from a hot cathode which had been freed completely from gas. Irving Langmuir's studies[2] of electron emission from hot tungsten lamp filaments demonstrated, however, that electron emission not only persisted in high vacuum but was favored by getting rid of the last traces of gas in the filament and other parts of the tube. Thus he was able to realize conditions which were stable and reproducible.

Coolidge,[4] encouraged by the work of Doctor Langmuir, developed an X-ray tube with a hot tungsten filamentary cathode and a solid tungsten target. He found that, even with the relatively high voltages and large masses of metal involved, it was possible to get and to maintain a vacuum sufficiently high to permit stable and reproducible operation.*

The relation of the current to the impressed voltage in a tube of this type is shown in Figure 1. The different curves are for different filament temperatures and show that, over the operating range of X-ray voltages, the discharge current is practically independent of voltage.

In one of the first Coolidge tubes (Figure 2A) the cathode consisted of a spiral tungsten filament mounted behind a centrally perforated tungsten or molybdenum focusing disk. Both filament and disk were set in the cathode side arm and the anode consisted of a circular tungsten disk attached to the end of a tungsten support rod. From the earliest form the design soon changed to that shown in Figure 2B, with its different cathode construction and its more massive target.

J. E. Lilienfeld[6] later developed a type of hot-cathode tube in which the primary electrons were produced from a hot filament in a side tube, the so-called ignition chamber. These primary electrons were caused to bombard the inside of the perforated main cathode where they liberated secondary electrons. The electrons passing through the perforated cathode were accelerated, by the high electrostatic field, toward the target with the production of X rays. The tube was more complicated than the simple hot-cathode type and apparently had no advantages over the latter.

In the gas tube the emission of electrons from the cathode was produced by positive ion bombardment, and in the hot-cathode tube by thermionic effect.

Experimental phenomena involving the pulling out of electrons from cold metals by high potential gradients have been observed and studied by many investigators.*[7]

H. A. Rowland, N. R. Carmichael, and L. J. Briggs[8] made early experimental tubes in which the cathode and anode consisted of aluminum wires mounted with their co-operating ends only a millimeter apart. With the best vacuum which they could produce, they found that current would pass through such a tube between the ends of the electrodes, generating X rays at a minute point on the end of the electrode which functioned as anode.

R. W. Wood[9] found that he could pass discharges from an induction coil between platinum spheres 1.5 millimeters in diameter placed 1 to 5 millimeters apart in a highly evacuated chamber over mercury, and that very penetrating X rays were produced at the anode sphere. The experiments of both Rowland and Wood were examples of field-current discharge.

Lilienfeld[10] developed an X-ray tube of this type in which the cathode was a wire with a pointed tip placed a few millimeters from the target and facing a depression in the target which served as the focal area. The function of this depressed area was to localize the focal spot which otherwise wandered about.

C. M. Slack and L. F. Ehrke[11] have developed a field-current tube for very rapid roentgenology which, for example, will depict a bullet in flight in its passage through an obstacle.

The electrical characteristics of the field-current tube resemble those of the gas tube in that the current and voltage are not independent of each other. Like the gas tube, therefore, it does not have the flexibility of the hot-cathode tube nor does it have its stability.

The main advantages of the hot-cathode high-vacuum tube over the gas tube are:

1. Flexibility; voltage and current may be varied independently at will.
2. It can be designed for much higher voltage.
3. Electrical stability permits more accurate reproducibility of results.
4. Nonvarying size and position of focal spot.
5. For a given energy input the tube can be made much smaller, thus facilitating X-ray protection and giving increased latitude in the design of auxiliary equipment.
6. Design of tube permits greater flexibility in use of hollow-anode construction to facilitate adequate X-ray protection, to reduce scattered and stray radiation, and to generate X rays at any desired location in the vacuum envelope.
7. As visual inspection during operation is not required, it can be enclosed entirely and out of sight, thus facilitating both electrical and X-ray protection.
8. Operation can be directly from a transformer without auxiliary rectifying device, thus making possible a very simple outfit which can be used for many purposes.
9. Long life.

Many forms of hot-cathode tubes of the high-vacuum type now have been de-

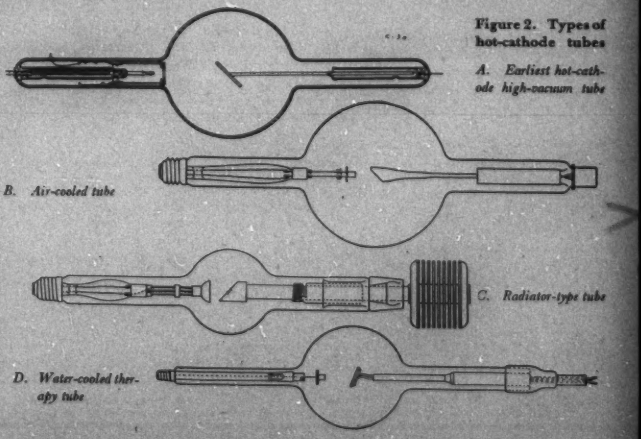

Figure 2. Types of hot-cathode tubes

A. Earliest hot-cathode high-vacuum tube

* K. T. Compton and I. Langmuir have reviewed the results of this work on field currents.

* The idea of using a hot cathode in an X-ray tube was not new at this time, but the principle had never been successfully applied in a vacuum so good that positive ions did not play either an essential or harmful role. The hot cathode of A. Wehnelt and W. Trenkle[5] employed a lime-coated hot cathode as a main electrode, but was not operable at useful X-ray voltages

veloped to cover a wide range of usefulness. They vary in size from that of an oil-immersed dental tube with a bulb diameter of $1^1/_2$ and a length of 4 inches, up to that of the 1,400,000-volt tube at the National Bureau of Standards, which is 12 inches in diameter and 24 feet long.

The "universal" tube with a solid tungsten target is a form that has been used for both diagnostic and therapeutic purposes for many years. As its target may get very hot, it is intended to be operated only with rectified current.

Another typical design, for diagnostic work only, is a radiator-type tube, shown in Figure 2C, built with a copper-backed tungsten target. It operates over a wide range of energy ratings and is capable of rectifying its own current provided the energy used is not sufficient to heat the focal spot to a temperature at which appreciable electron emission would take place.

Another typical type, with a high energy rating for continuous operation, is a water-cooled tube (Figure 2D) especially developed for therapeutic use while for internal body-cavity work[12] a special form of therapy tube has been developed.

For use at very low voltages (approximately 1,000 to 10,000 volts) thin beryllium windows may be utilized.

The electrons are emitted from a hot tungsten filament, and the tube can be so designed that the current flowing from cathode to anode is either emission limited or space-charge limited. In the former case, over the operating range of voltage, all of the available electrons from the filament are used and the milliamperage is, therefore, dependent only on filament temperature. In the latter case, the filament always is operated at a temperature in excess of that required to emit the desired number of electrons and the milliamperage is limited by the negative space charge due to the electrons. The amount of this space charge is determined by the electron velocity and so by voltage used.

The tube used for the data contained in Figure 1, when operating with a filament current as high as 3.6 amperes, was evidently emission limited from about 50 kilovolts upward, while for lower voltages it was space charge limited.

For maximum flexibility, it is desirable to design the tube to be emission limited in order that any desired current can be used with any desired voltage. With a space-charge-limited tube, the lower the anode voltage, the less current can be made to flow through the tube.

With an emission-limited tube the current changes very rapidly with filament temperature as shown in Figure 1. This makes it desirable to have a constant source of voltage to heat the filament. Storage batteries were used at first, but since have been replaced generally by transformers for filament excitation. The effect of fluctuations in line voltage is minimized by some form of stabilizer such as the Kearsley[13] or constant-current transformer type.[14]

The hot-cathode tube, unlike its predecessor, permits the independent control of the quality and intensity of X-ray output. The quality is determined primarily by the applied voltage and secondarily by wave form and target material. It is also somewhat dependent on the angle, referred to as the tube axis, at which the X rays are emitted. These conditions all being fixed, the intensity is simply proportional to the current.

The X rays produced are in general of two kinds; those characteristic of the target material, and those which are independent of target material and, like white light, include a considerable range of wave lengths. Of the latter, the shortest wave lengths, λ_0, bear the following simple relation to the voltage:

$$\lambda_0 = \frac{12{,}340}{\text{voltage}}$$

in which λ_0 is expressed in angstrom units (1 angstrom $= 10^{-8}$ centimeters). For practical purposes, the *effective* wave length in general can be considered to be about twice the minimum value.

In comparison with visible radiation, which lies between 4,000 and 7,000 angstroms, X rays in use today range in effective wave length from about 0.00025, corresponding to 100,000,000 volts, to 25.0 angstroms, corresponding to about 1,000 volts. Table I gives the voltage range and the corresponding effective wave lengths of radiation for various medical purposes.

In the hot-cathode high-vacuum tube, even with perfect focusing of the primary electrons, there is in general a considerable X-ray production from the surface of the target outside of the focal area.[15] This is due to high-velocity secondary electrons emitted from the focal spot. They cannot go, as in the gas tube, straight to the glass walls, as these are, in the high-vacuum tube, relatively close to cathode potential. They must therefore return to the anode where their impact gives rise to the Roentgen radiation which may be observed, by means of a pinhole camera, as coming from other than the focal area. For diagnostic purposes this parasitic radiation would be troublesome if it were much more intense than it is. Its effect, however, could be reduced if necessary by special design.

The intensity of the rays is dependent upon their direction with respect to that of the cathode rays which produced them and the relation of these two quantities is affected strongly by the voltage used. At voltages much below 1,000,000 it is customary, for most purposes, to use X rays emanating from the face of the target. It is convenient to designate these rays as the "reflected rays." With higher voltages the rays passing through the target ("transmitted rays") are employed more often. In the case of tubes intended for use in body cavities and employing relatively low voltages, transmitted rays ordinarily are used. Penetrating power also is affected by direction of emission but not to as great an extent as intensity.

Measurement of the intensity of the reflected rays from a universal tube showed[16] a maximum in close to the direction of the generally used "central ray," decreasing to half this value at an angle (measured around the girdle of the tube) of about 75 degrees on either side. This was with a voltage of 127,000. Petrauskas, Van Atta, and Myers,[17] using the unfiltered "transmitted" beam from a target placed at right angles to the cathode rays, found at 2,350,000 volts maximum X-ray intensity close to the central ray dropping to half

Table I

Application	Voltage	Effective Wave Length (Angstroms)
Dental roentgenography	50,000–70,000	0.5 to 0.4
General roentgenography	50,000–100,000	0.8 to 0.24
Therapy	1,000–1,000,000	24.7 to 0.025

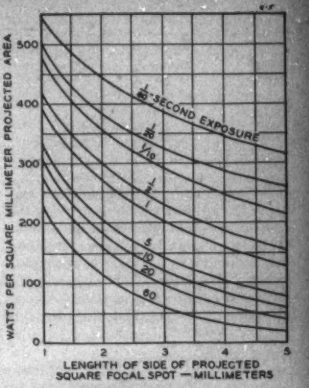

Figure 3. Tungsten-target focal-spot loading data

Single phase, full wave, 60 cycles; line focus 20-degree target angle

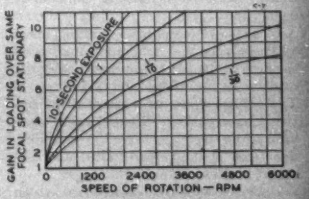

Figure 4. Gain from rotation of target

Table II

Voltage (Millions)	Efficiency (Measured, Per Cent)	Efficiency (From Theory, Per Cent)
2.55	10.4	8.3
1.65	5.8	5.6
0.90	3.0	3.4

value at about 37 degrees from this direction. Doctor Kerst,[18] working with the induction electron accelerator at 20,000,000 volts, found the intensity dropping from maximum to half value in about four degrees. With the 100,000,000-volt induction electron accelerator operating at full voltage, the corresponding angle is only one degree.[19]

EFFICIENCY OF X-RAY PRODUCTION

The efficiency is directly proportional to the atomic number of the target metal and increases rapidly with voltage. Rutherford and Barnes,[20] operating a hot-cathode tungsten-target tube from a static machine, obtained at 96,000 volts an efficiency of transformation of cathode-ray energy into X-ray energy of 0.2 per cent.

In Table II recent measurements made by Petrauskas, Van Atta, and Myers, with the help of the large Van de Graaff static machine at the Massachusetts Institute of Technology, show the dependence of efficiency upon voltage. The rays were taken from a gold target and in the forward direction (that of the cathode rays) and corrected for absorption in the target.

Under normal conditions, current can pass through the tube in only one direction. If, however, any portion of the focal spot is allowed to become heated to the temperature of the cathode filament, on a-c excitation, current will flow through the tube in both directions. The resulting electron bombardment of the cathode will raise its temperature, thus increasing the target bombardment, and so cause runaway. While, then, the tube may be operated satisfactorily from alternating current, serving as its own rectifier, with any given design the capacity of the tube is always greater when operating from a unidirectional source.

Even with rectifier current, the energy input must not be so high as to cause appreciable vaporization of the tungsten from the focal spot because the tungsten vapor, by becoming ionized, may cause instability, signalized by rapid rise of current.

TUBES FOR ROENTGENOGRAPHY

For the production of radiographs of the highest technical quality the tube should be so designed and constructed as to permit the production of the greatest possible X-ray intensity, consistent with satisfactory tube life, from a given size of focal spot. The target in most general use is the composite one developed earlier for the gas tube which has a tungsten facing of a certain thickness in good thermal contact with a large mass of copper. The copper with its high heat conductivity serves to take the heat away rapidly from the focal spot, distributing it to its large mass which serves as a reservoir, from which it can escape later by radiation and conduction before the next operation of the tube. The thickness of the tungsten facing will be chosen just sufficient to prevent the melting of the copper at its hottest point just behind the focal spot.

In this same connection, cathode design is also important as it determines not only the size but also the distribution of energy over the focal spot. This last must be as uniform as possible because, for a given area, the limit to allowable energy input is set by the hottest part of the focal spot.

For the maximum possible X-ray intensity per unit of focal area, direct current at constant potential would be employed to operate the tube. As single-phase a-c high-voltage apparatus is much simpler, however, it is used ordinarily. With a-c high-voltage supply, the maximum available intensity per unit area is appreciably greater if an auxiliary rectifying device, such as full-wave kenotron rectifier, is employed. Here again, however, a simpler system, in which the X-ray tube rectifies its own current, often is used.

In the line-focus tube[21,22] a rectangular electron beam is used to provide a projected square focal spot in the useful roentgenographic direction. The gain obtainable by this method[23] is determined by the minimum angle of the target face with the direction of the useful beam that will provide adequate film coverage for the largest film at the minimum distance to be used. In general, a 20-degree angle has been found to be the most practical for roentgenographic uses. For this, the gain over a 45-degree angle may be as much as threefold. In some special tubes 15 degrees are used and even 10-degree target angles have been employed. The gain for 15 degrees may be about fourfold and for 10 degrees as much as fivefold. The coverage at 10 degrees is, however, so small that a minimum six-feet target-to-film distance should be used. There is, furthermore, the disadvantage in the use of so small an angle as 10 degrees that the development, with use, of any considerable roughness of the focal area may cause serious loss of X-ray intensity in the useful direction.

Various subjects for roentgenography may require widely different amounts of radiation, as well as different limits in time of exposure. To facilitate the revelation of as much detail as possible in all cases, tubes are made with a variety of focal-spot sizes ranging from about one millimeter to nine millimeters. For focal spots of these sizes the allowable loading of a tungsten target three millimeters thick, cast in copper, varies from about 50 watts to 600 watts per square millimeter, depending on size of focal spot and time of exposure. Figure 3 gives safe values for tubes operating on single-phase full-wave rectified 60-cycle current. The smaller focal spots will stand higher specific loadings because the surrounding tungsten is more effective in heat removal from them than in the case of larger focal areas.

To simplify the technique of roentgenography of the various parts of the human body, double-focus tubes often are employed. In these tubes, by means of a double cathode, either of two radically different sizes of focal spot may be used. The smaller is employed to give fine detail in body extremities and the larger for thicker parts requiring more energy.

The loadings of a stationary target cannot exceed certain definite values safely. By rapid rotation of the target, however, relatively cold metal can be advanced constantly to take the electron bombardment, and so the permissible loadings can be increased greatly. Such rotation was suggested by R. W. Wood in 1897, and later by Rollins and Elihu Thomson. In 1915 Coolidge reported on experimental work with a tube in which the rotating target was supported by ball bearings and ran at 750 rpm, yielding a gain of twofold or threefold in the amount of energy which could be carried on a given focal area.

The target is rotated best by means of an induction motor whose stator is without and whose rotor is within the tube and carries the target. A commercial tube with a plain sleeve bearing which embodied this principle was described by Bouwers[24] in 1929.

Ball bearings, to be used successfully, must be made of metal which is hard at the temperatures to which they are subjected in this application. This requirement is fulfilled by certain precipitation hardening alloy steels.

In our early ball-bearing rotating-target tubes the drastic heat treatment required for the exhaust removed the last trace of lubricant from the bearings. As a result the friction was high and, to operate at all well, it was necessary that the bearings have appreciably more than the customary radial clearance. This made them very noisy. It since has been found that this difficulty can be overcome by coating the bearings either with a vaporized thin film of barium[25] or vacuum-coated silver.[26]

In the rotating-target tube rotation is combined with the use of the line focus. The gain to be derived by rotation is shown in Figure 4 for various speeds.[27]

In rotating-target tubes on the market today a speed of 3,000 to 3,500 rpm is

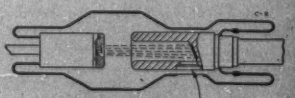

Figure 5. Self-rectifying therapy tube with hood anode construction

employed. The gain in loading as compared to a stationary-target tube varies with the exposure time and is about as the square root of the speed.

TUBES FOR FLUOROSCOPY AND THERAPY

In the medical field the same tubes used for roentgenography are, in general, suitable for fluoroscopy as the requirements of the latter service have been considered and met in the design of roentgenographic tubes. Most medical fluoroscopy is done with a current of two milliamperes to five milliamperes at voltages from 40 kv peak to 85 kv peak, depending upon the technique employed and the part of the body being studied. In this service the tube may be energized for a few seconds or for several minutes at a time.

For industrial fluoroscopic work special tubes may be required, as currents of as high as 15 to 30 milliamperes at voltages of 85 to 250 kv peak may be needed.

Because the detail recognizable in fluoroscopy is not as great as in roentgenography, exact size of focal spot is not as important as in the latter service. For the requisite long time of operation, the total heat developed is considerable, and the anode must be capable of handling it.

In therapy the main requisite is to provide a sufficiently large beam of the desired kind of radiation having essentially uniform intensity over its entire cross section.

The skin-focus distance, dictated in general by depth-dosage considerations, ranges from about 25 centimeters to 100 centimeters, and the largest field to be covered is about 20 centimeters by 20 centimeters.

The size of focal spot is relatively unimportant. Usually round, it varies from about one-quarter inch to one inch in diameter.

Therapy-treatment periods range from several minutes up to as much as an hour in special cases, so that the duty of the tube for all practical purposes must be considered as continuous. This means that the main design problem in tubes for therapy concerns the removal of heat from the anode.

This may be accomplished either by using a solid tungsten target and allowing this to heat up to a high temperature where it can radiate the requisite amount of energy, or a composite tungsten–copper target may be cooled by rapidly flowing water or oil. In the case of oil-immersed tubes a heavy anode stem may be employed to conduct heat out to the oil where it may be dissipated by natural convection.

The voltage employed in superficial therapy may be as low as 5,000 or 10,000, in which case the radiation would not be transmitted to a useful extent through the ordinary glass envelope. For such work a thin window of beryllium may be used.

Voltages from 200 to 400 kv peak make possible the treatment of the deepest seated tumors found in the body. Tubes produced today for these voltages have a thick-walled pyrex envelope to avoid puncture. They usually are cooled by circulating oil in the back of the target and at 200 kv well may carry as much as 10 or even 30 milliamperes.

They may be operated from either a rectified- or unrectified-current source. The performance of such tubes, when operating directly on alternating current, is improved considerably by the use of a hooded target, as shown in Figure 5. The presence of the hood reduces the number of secondary electrons emanating from the target and reaching the glass envelope where otherwise their presence in sufficient number might lead to puncture.

For 400,000 volts, tube design is much the same as for 200,000 volts except that all physical dimensions have to be increased. At this voltage, less current is required in general and at present five milliamperes is in common use.

During the last few years much interest has been shown in the therapeutic use of voltages of 1,000,000 or more. For such voltages, and even for much lower ones, the tube can be sectionalized to advantage[28] and provided with a multiplicity of hollow accelerating electrodes. This gives a more uniform gradient along the length of the tube and reduces dielectric stresses in the glass envelope. At the same time it serves to prevent the formation of troublesome field currents which otherwise may take place from the cathode due to the stronger field which exists there in case only a single pair of electrodes is used. The accelerating electrodes usually are connected to suitable taps in the high-voltage source. With such high voltages the target may be so designed as to make possible the use of either the radiation coming through the target or that given off from the face. At these voltages the intensity is greater in the "transmitted" than in the "reflected" beam and the effective wave length is shorter.

Such tubes may be operated either while undergoing continuous evacuation from a suitable pumping system or sealed off.

This was followed by commercial transformer installations in which the tube consisted of a multiplicity of cylindrical glass sections cemented or sealed together and provided with hollow cylindrical accelerating electrodes.

With the advent of the low-frequency resonance transformer,[29] it became possible to put the tube inside of the transformer. This location facilitates the connection of the various accelerating electrodes to the transformer and at the same time provides electrostatic shielding for both the tube and the connecting leads.

An early 1,000,000-volt example of this type of equipment was installed in 1939 at the Memorial Hospital in New York.[29] It was stationary and arranged for therapeutic use with either the reflected or transmitted beam. It was a 12-section tube and was pumped continuously.

A later similar 1,000,000-volt outfit,[30] developed originally for industrial roentgenography, is smaller, has a sealed-off tube, and can be operated in any position. A similar outfit,[31] also with sealed-off tube and operable in any position, has been developed for 2,000,000 volts. It seems entirely feasible by this method to go still higher to perhaps as much as 4,000,000 or 5,000,000 volts.

For X-ray diffraction work it is desirable to have radiation which, as nearly as possible, is monochromatic. This is obtained by using, not the general Roentgen radiation, but that characteristic of the target material. As for different purposes different wave lengths are required, this necessitates the use of tubes with different target metals, such as copper and molybdenum. The voltages used for these two metals are usually 30 to 35 kv for copper and 35 to 45 kv for molybdenum and the characteristic wave lengths are 1.539 angstroms for copper and 0.709 angstrom for molybdenum. These radiations usually are taken out through thin beryllium windows.[33] To increase the capabilities of the diffraction tube, it may be provided with a number of windows, thus making possible the simultaneous study of a corresponding number of specimens.

THE PROTECTION PROBLEM

Protection must be provided from both the X rays and the high voltage. This is accomplished much more readily with the modern type of tube than with its predecessor, and for two reasons. First, the modern tube, for the same service, can be much smaller than the gas tube, and, second, it does not need to be seen during operation.

As X rays are emitted in all directions from the front of the focal spot, lead, or its equivalent, is used either in the walls of the tube or in the tube enclosure to absorb all but the useful beam. The electrodes of the tube usually are sufficiently massive to guard against most of the radiation which otherwise would escape from the ends.

X-ray protection was secured readily in the "Metalix" tube[32] of the Philips Company, with its grounded metal envelope surrounding the central portion, Figure 6. The same result also was secured by the construction in which the radiator-type tube was provided with a two-piece thick-walled shield of glass having a high lead content.

The small tube developed for medical diagnostic use with a portable outfit, derives its X-ray protection from its very thick

Figure 6. "Metalix" tube

envelope of glass which has a high lead content. The useful beam of rays was taken out through a leadfree glass window.

In tubes in which the target is located in a metal extension chamber attached to the tube envelope and, more particularly, in one and two million-volt tubes in which the X rays are transmitted through the target as well, X-ray protection is facilitated, to a great measure, by surrounding this chamber with an adequate wall of lead.

Full electrical protection is obtained by enclosing the entire high-voltage circuit in grounded metal. Two different methods are used for obtaining this result.

One of these is a small Roentgen tube, together with filament transformer and high-voltage transformer, all in the same oil-filled metal case. Such a system is used extensively for dental work, therapy, and other applications. In some cases, compressed gas is used in place of oil for the high-voltage insulation.

The other method of securing electrical protection consists of housing the tube in a grounded oil-filled metal enclosure, and connecting it to the high-voltage source by means of heavily insulated flexible metalclad cable. For rapid medical roentgenography this method is preferable to the former, as it permits the use of a powerful high-voltage source of rectified current while retaining relatively light weight in the part which has to be moved, namely, the tube and its enclosure.

With both systems lead, or its equivalent, will be used around the tube and the metal enclosure can be made not only to provide electrical protection but also to increase the X-ray protection.

For the production of X rays corresponding to voltages in excess of a few million, the induction electron accelerator is today the most attractive looking device. It has proved successful in the 20,000,000-[10] and the 100,000,000-[10] volt sizes and presumably can be used for higher voltages.

The tube is a hot-cathode high-vacuum device consisting of a hollow toroid of glass or other insulating material about 18 inches in diameter for the 20,000,000- and six feet in diameter for the 100,000,000-volt sizes. The electrons from a hot filament are focused electrostatically and are accelerated with some 20,000 volts or more in a direction tangential to the axis of the toroid. By means of a time-varying magnetic field they are accelerated further and focused and constrained to follow a circular path within the tube. In the case of the 100,000,000-volt machine they encircle the field 250,000 times in 1/240 seconds, receiving on an average a 400-volt push each time around. After traveling in this circular path for about 800 miles and receiving the energy which they would have had if they had passed between two electrodes having a potential difference of 00,000,000 volts, they are caused to leave their circular orbit and impinge upon a tungsten target where they produce X rays. Or they may be caused to leave the circular orbit at any desired earlier time in the magnetic cycle, thus producing X rays corresponding to any voltage up to 100,000,000.

The electron current in the beam is very low compared with that which ordinarily has been used in Roentgen tubes and of the order of a microampere, depending to a great extent on the frequency employed for the time-varying magnetic field.

The tubes may be built either as unitary structures or in sections cemented together and continuously pumped. The 100,000,000-volt tube consists of 16 pie-shaped sections of heat treated pyrex glass having an elliptical cross-section of 8 inches by 4⅞ inches. The ends of the section are ground flat and smooth and to the correct angle, and the joints, coated on the outside with glyptal paint, are vacuum tight.

The induction electron accelerator, as a multimillion-volt X-ray source, will be used extensively in scientific research and also should find therapeutic and industrial applications.

SUMMARY

During the 50 years since Roentgen's great discovery, the X-ray tube, from a very uncertain and relatively feeble source of radiation, has been developed into a powerful precision tool of great stability, flexibility, and ease of control, permitting accurate reproducibility of results and capable of operation over a very wide range of current and voltage. In the diagnostic field, definition, for a given speed, has been improved greatly through the years. For therapeutic work the high-voltage rays now obtainable make possible the treatment of deepseated lesions. The various industrial applications make use of the entire range of wave lengths which can be derived from the tube, at least corresponding to voltages up to a few million. The gradual increase which has taken place in the allowable voltage has been attended by a corresponding extension in the range of usefulness of the rays in industry. Much X-ray protection now can be built into the tube itself, and the modern tube lends itself readily to the attainment of complete electrical protection. From the point where only an expert, with years of experience, could obtain the best results, the X-ray tube has developed into an instrument which is as easy to operate as an incandescent lamp.

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Industrial X-Ray Developments

C. D. MORIARTY

Advances in the production of X-ray materials, techniques in the recording of X-ray results, and the opportunities for the electrical engineer in the field of industrial X-ray equipment are discussed in this review of an application of the rays whose powers were first observed by William Conrad Roentgen a half century ago.

IN a consideration of industrial X-ray developments it is necessary to go back 30 years, and to stress particularly the influence of World War I on medical X-ray equipment and technique. At the outset it can be said that portability of equipment was a prime requirement, and with patience, perseverance, and diligence the objective was achieved.

Now, another world catastrophe has influenced the field of the X ray, and the termination of World War II finds many advances and improvements in the production of X-ray materials and the techniques of application. Not the least among these are:

1. Raising the operating potential of X-ray equipment first to 1,000,000 volts and then to 2,000,000 volts.

2. Production of new X-ray film to extend the use of this high voltage.

3. Broadened application of the X-ray technique of visual inspection of industrial products.

4. Application of photoelectric equipment to industrial units.

RECORDING X-RAY RESULTS

Fundamentally, there are three techniques of indicating or recording industrial X-ray results. They are:

1. Radiographic method. This is the chemical development of a resultant latent image on an X-ray film. The method combines high sensitivity with ease of interpretation of the results, and provides a permanent record. It is, however, relatively slow and costly.

2. Fluoroscopic method. A visual examination is made of a chemically coated screen which gives off visible light in proportion to the quantity of X rays impinging on it. This method combines ease of interpretation of results with speed and low cost. It is, however, of low sensitivity.

3. Electrical method. This is the varying of electric current in proportion to X-ray radiation by means of a phototube or by ionization. The newest of methods, it combines highest sensitivity with speed and low cost. The results, a summation of several possible variables, may be difficult to interpret.

RADIOGRAPHIC EXAMINATIONS

The time is not far distant when radiography of small parts will resemble present blueprinting methods, using a low-voltage high-current X-ray source. Instead of employing the slow stop-and-go technique, the objects being radiographed will be in constant motion. Such a procedure already is being used. Figure 1 shows the application of the method using 1,000,000-volt X rays.

Advantages of continuous motion are readily appreciated. The speed of the conveyor governs the time of exposure for a given thickness of material; the useful life of the X-ray unit is extended since the on-off cycles are eliminated or considerably reduced, and the variable in time of bringing up the voltage is eliminated. This makes for uniformity of results. Such methods of radiography require a powerful source of X rays, either in voltage or current, to counteract the relative slowness of X-ray film if normal conveyor speeds are to be maintained.

FLUOROSCOPIC METHODS

When records are desired, or careful analysis and interpretation needed, radiographic examinations will be required. However, the fluoroscopic method approximates the radiographic method except that it leaves no record. It is less sensitive, but is limited in speed only by that of the human eye. Within the limits of present fluorescent screens there are many places where fluoroscopy is applicable, even though more power is required than for radiography, and even though the resultant detail is not so good. It is ideal for rapid X-ray examination of small parts prior to machining, since it will show whether internal defects will interfere with machined, drilled, or tapped areas. It is a low-cost method sorting out grossly defective material, and avoids a waste of time on subsequent costly examinations such as radiography.

Just as in the case of radiography, the trend in fluoroscopic examination is for continuous motion, as shown in Figure 3. The X-ray source in such installations is usually a low-voltage high-current unit. The supporting structure for fluoroscopic examination consists of plastic trays on a race-track type of conveyor. The objects, resting on turntables mounted on these trays, rotate while they travel between the X-ray source and the fluorescent screen. Over the fluorescent screen is an inch-thick plate of lead glass which prevents X rays from reaching the operator but permits efficient transmission of visible light from the screen.

Hundreds of thousands of objects have been examined fluoroscopically with the unit illustrated in Figure 2. Where interpretation or the nature of nonhomogeneous masses is the paramount question, the unit is used as a visual inspection tool. The eyes of the operator then are the limiting feature in speed and sensitivity. When considering the possibility of increasing the effectiveness of fluoroscopy, it should be remembered that there is always the hope of finding some fluorescent substance that will give off more visible light when exposed to X rays.

ELECTRICAL METHODS

In the field of electronic recording of X rays the future is particularly promising. One reason is because the field is relatively new.

The ability of X rays to ionize gases is well known, and has been applied advantageously in ionization-chamber methods of detecting and measuring X-ray strengths. Practical considerations encountered in industrial plants have, however, held back application of the ionization method to industrial inspection. Since 1912, with the advent of the Coolidge tube, X rays have been created in a high vacuum. Now it seems reasonable to expect that they will also be detected in high vacuum, just as visible light is detected today with a high-vacuum phototube.

Among recent new electron tubes is the multiplier phototube, combining an amplifier and a phototube in one unit. Itself a highly sensitive detector of visible light, it

Figure 1. One-million-volt X-ray equipment for inspecting 155-millimeter shells at Ravenna ordnance plant, Apco, Ohio

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may be used indirectly for X rays. By the addition of a fluorescent substance on the transparent glass envelope of the multiplier phototube, this tube, opaque to external visible light, becomes a sensitive detector of X rays. The effects of temperature and humidity on the fluorescent substance under X-ray conditions need thorough investigation before results can be evaluated in absolute terms; but already the device has been put to several practical applications.

The first X-ray inspection job to which the multiplier phototube was applied served to illustrate its potentialities. Hand-grenade fuses were carried on a conveyor so as to intercept an X-ray beam aimed at the phototube (Figure 3). The phototube was given one-fifth second in which to determine:

1. If the fuse contained the proper powder charge.
2. To record the information on a photoelectric recorder.
3. To activate a thyratron (if there were insufficient powder), which in turn controlled a stamping device to mark any defective fuses.

Three quarters of a million fuses were thus tested in very short order. The rate of testing—4,000 per hour—was not limited by electrical but rather by mechanical characteristics of the particular setup.

On the basis of such a method, many new applications suggest themselves. Some of the present-day fluoroscopic examinations, such as the ones used on citrus fruits and canned goods may be converted advantangeously to this automatic method. Like most electronic developments, the new method introduces speed and sensitivity into a field heretofore paced by time exposures in radiography or endurance of the human eye in fluoroscopy.

Another interesting application of the phototube method was the inspection of a large turbine rotor (Figure 4). The steel forging was 13 inches in diameter, with a hole 2 inches in diameter made lengthwise through the center and "dead-ended" inside. The problem was to check for nonhomogeneous masses, and to measure any eccentricity of the two-inch bore. The thickness was too great for radiography or fluoroscopy, but previous tests of the phototube with 1,000,000-volt X rays had shown good results on 12 inches of steel.

The phototube was inserted in the bore and the 1,000,000-volt X ray was pointed at it; the rays had to penetrate a radial thickness of about six inches to reach the tube. The rotor was turned at constant speed during examination, the phototube and X-ray source remaining fixed in positions. The output of the phototube was supplied to a photoelectric recorder which charted any change in radial thickness and hence any eccentricity of the bore.

Photoelectric circuits may be used in industrial X-ray work for control purposes as well as for recording. They can automatically control the amount of exposure an X-ray film is to receive (Figure 5) or the brilliancy of a fluorescent screen. Such control applications should take much of the uncertainty out of industrial X-ray

Figure 2. X-ray fluoroscopic unit for examination of light-alloy castings

Figure 3. Phototube method of high-speed inspection of hand-grenade fuses

Figure 4. Phototube method of inspecting turbine rotor for eccentricity of bore (phototube unit on end of rod)

Figure 5. Proper X-ray film exposure is assured by the phototube shown against the back of the film holder

laboratories. Variations in X-ray voltages, current, distance, thickness, or the kind of material will be taken into consideration automatically by phototube control.

COMBINATION METHODS

Most industrial X-ray examinations are made to answer either or both of two questions: "Is the material homogeneous?" and "If not, what is the nature of the nonhomogeneity?" It is the answer to the second question that is time-consuming and therefore a costly item in X-ray examination. By the same token, the value of an X-ray examination over other nondestructive methods is its ability to answer this second question. Either radiography or fluoroscopy will supply the answer to this question; the electrical method of recording X rays provides the best means for answering the first question.

Why not, therefore, combine the different methods? Let there first be an exploration with the electrical method, with interpretation where necessary with radiography or fluoroscopy. It can be done; in fact, Figure 3 shows a performance of both electric and fluoroscopic examinations. Such a combination of methods to be successful must have each method working at highest speed consistent with efficiency. Here again is where continuous motion of the object under examination comes into play.

Motion and photoelectric circuits in industrial X-ray work are among the major advances to be expected in the near future. Their possibilities are indicated by some of the jobs already done, and additional applications depend only on the ingenuity of the electrical engineer.

X Rays an Early Institute Topic

IN 1895 William Conrad Roentgen observed an invisible radiation which penetrated substances opaque to all other known radiations. In AIEE *Transactions* for the following year are recorded some of the first technical discussions of the subject. These now assume renewed interest in relation to the accumulation of knowledge since that time.

A meeting of western members of the Institute was held at Chicago, Ill., on March 25, 1896, for the purpose of exchanging information on the new ray. Charles E. Scribner presented a historical sketch of the discovery, and described experiments made by him and the apparatus used. Doctor James Burry also spoke on "The Surgical Value of the Roentgen Ray." Wilbur M. Stine* presented details of his experiments, discussing the point of formation of the rays, penumbral effects, polarization of the rays, sensitivity of photographic plates, and other matters. He concluded:

"Much stress has also been placed on fluorescent glass bulbs as the source of the ray. To test this a cube of uranium glass was powerfully excited by a focused arc light, but only negative results were obtained in repeated and lengthy exposures. The surface of the cube was also kept charged by a Holtz machine, but no results were obtained. The fluorescence of the bulb of the Crookes tube seems rather an accidental than a causative phenomenon. The kinematics of the Roentgen ray was carefully and exhaustively studied. In short, no evidences were found of diffraction, refraction, reflection, or interference. There are many appearances of such character, which have evidently misled some rather untrained experimenters, yet when carefully studied are found of negative value."

At the 111th meeting of the AIEE on

One of the leading subjects presented at Institute meetings a half century ago was the newly discovered X ray. These excerpts from the words of men whose names became recognized as being among the leaders in electrical engineering emphasize the advances in scientific knowledge that have been made during the ensuing years.

December 16, 1896, at New York, N. Y., there was a topical discussion "The Roentgen Ray, and Its Relation to Physics." In opening the discussion, Henry A. Rowland† said:

"A gentleman asked me a few moments ago if I knew anything about the X rays. I told him no; that what I was going to tell tonight was what I did not know about the X rays. I do not suppose anybody can do much more than that, because all of us know so very little about them. We were very much surprised, something like a year ago, by this very great discovery. But I cannot say that we know very much more about it now than we did then. The whole world seems to have been working on it for all this time without having discovered a great deal with respect to it."

His discussion foreshadowed subsequent applications:

"Now, one important point with respect to these rays is as to whether they are homogeneous. Are they like light which can be divided up into a large number of different wave lengths, or are they homogeneous? There seems to be a great deal of evidence that they are not all the same; that one ought to get a spectrum of them in some way . . . there seems to be little reason to doubt that a number of rays really do exist; that whatever they are that come from the object, they are not all the same; some of them penetrate bodies better than others, and very likely someone will get up some sort of filter that will filter them out, and allow us to use them and to find if they have different properties. At the present we are rather in the dark with regard to this point."

He also gave credit to an earlier scientist:

"I must say that Lenard, when he first experimented upon this subject—and I regard his experiments as quite as valuable as Roentgen's, probably—, he got several kinds of rays coming out through an aluminum window. He got rays which were deflected by the magnet, as well as others. He had not separated them however. When the Lenard paper came to the laboratory I remarked to my students: 'That is the best discovery that has been made in many a day.' I immediately set somebody to work experimenting. He tried to get some results and would probably have discovered the Roentgen rays at that time if it had not been that the University of Chicago called him off, and Johns Hopkins University was very poor and could not call him back, and he had to stop in the midst of his work."

Describing means of excitation for the tubes, Elihu Thomson‡ said:

"But the most effective method of excitation which we have yet been able to use has been one of which the public has heard nothing so far and I mean to speak of it now. It was arranged by Mr. Hermann Lemp (whose name is familiar to many of you) in this way: He simply took a 12-inch inductorium, a coil giving a 12-inch spark ordinarily, and excited the primary with alternating cur-

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† Professor of physics, Johns Hopkins University, Baltimore, Md.

‡ Electrician, General Electric, and Thomson Electric Welding Companies, Lynn, Mass., and AIEE president, 1889–90.

rents at 125 cycles. This gives in the secondary, as in any step-up transformer, a great increase of potential, such that we may find that the spark darts five or six inches between terminals, and, of course, after it is started, there is a continuous arcing somewhat difficult to stop unless you blow it out or shut off the current, which latter is probably the easiest way. Now this high potential discharge of the secondary is, of course, an alternating current—an alternating current somewhat of the same wave form as the impressed primary wave. But if we rotate, by a little synchronous motor, a break piece which picks out one direction only of the secondary discharge and leaves that in the other direction open-circuited, then you see we have an admirable source of uni-directional discharges of great power. Of so great power indeed are they that you would not dare to put them upon your Crookes tube without modification. You must put up a high resistance, such as a water resistance—a long glass tube filled with water—to cut down the flow which would destroy almost any tube you might try. The commutating device made properly simply consists, for example, of two insulated terminals in series with the discharge, and a connecting wire revolving synchronously between them. With a spark gap between the wire and fixed terminals, of course we do not need friction or any contact. You are then chopping off the tops of the waves or are taking the very highest potential of each and every wave all in one direction, and you are also giving them a spark gap between the fixed terminals and revolving wire which is favorable to the generation of the rays. The spark gap regulates itself in a measure, because just as soon as the potential is such that it can easily jump a gap then the commutator wire anticipates the discharge and the current leaps the spark gap. If there should be a weaker discharge, the wire comes up nearer to the terminals before the gap is jumped, so that in this case the discharges are wonderfully uniform and you get them at the rate of 125 per second, which is a rapid rate, and excites tubes wonderfully well."

He indicated the difficulties which beset the early experimenters:

"We often come across very curious things in this work with different forms of tubes under different conditions, and I think there is hardly a more fascinating field than working with these vacuum tube arrangements. There are no two alike. You can hardly produce the same exact effects twice. I may mention a curious thing which I noticed the other day. We had a spherical bulb with a wedge of platinum, the cathodes opposite each other. We made one of these actual cathodes, and the platinum the anode, with commutated current excitation. The vacuum in the tube was a little low, and one would suppose that the side of the platinum nearest the real cathode would get hot, but I was astonished to find that there was a bright spot on the other side opposite the idle cathode and none on the side opposite the real cathode. The latter side was not even hot, but the apparently idle cup on the other side of the tube had sent out something or other which produced a red hot spot opposite to it and gave rays. That is only one of the curious things we find, which among the many others serve to mix us up and carry us perhaps farther away from the real thing that we all are looking for."

His experiences also showed the risks to which these pioneers were exposed:

"I was interested some time ago in regard to the effect of Roentgen rays on the tissues. I had read a few times that certain people had been burned by Roentgen rays. I did not believe it. These rays went through tissue so easily that their action could not amount to anything, but it was certainly worthwhile investigating so as to know. So I used a tube, which happened to be a heavy blue glass tube with a clear glass window. The blue glass did not allow the rays to get out, and they were absorbed except through the clear glass portion, where I wanted them for use. I put my finger up to the clear glass window and kept the other fingers pretty well shielded by the blue glass of other parts of the tube. I exposed the finger for half an hour to the rays, a Holtz machine being the source of electricity. I put the finger up pretty close to the tube, and after half an hour I thought that perhaps it was not long enough; perhaps it was not half enough. But if there were to be any effect it would be equivalent to a few hours distance, and as I got tired I went no farther. I shut down the tube and went away. Five, six, seven, eight days passed and nothing happened, and I felt that people had been mistaken about the effect of the rays. But on the ninth day the finger began to redden; on the twelfth day there was a blister, and a very sore blister. On the thirteenth or fourteenth day after exposure, the blister had included all the skin down to the part not exposed and had gone around the finger almost to the other side. The whole of the epidermis came away and left an ulcer without any possibility of recovering its own epidermis except from the edges, and I had to go through that painful process of having a raw sore there and the epidermis growing in from the side and gradually closing up. Only three days ago was the sore actually closed, and the skin is yet very tender, and nature does not appear to have found out how to make a good skin over that finger."

Michael I. Pupin* described some of his experiments and discussed the various views on X-ray theory, particularly a theory of Helmholtz which called for bodily movement of the ether. A. E. Kennelly† then said:

"Just one word about the theory of the subject. Whatever may be the nature of the Roentgen ray, it must be either a bodily movement of matter, or a movement of a disturbance in matter, or a bodily movement of ether; or, finally, a movement of a disturbance in ether. As regards the first supposition, that X rays are streams of matter in motion, or of projected molecules, there is an experiment which seems to negative it. A Crookes radiometer vane does not, as far as I have been able to discover, recede from an excited Roentgen ray tube. One would suppose that it would be powerfully repelled, if X rays were bombarding streams of particles . . . . As regards the three remaining hypotheses, it is to be hoped that future researches will show that X rays are ultra-ultra-violet light rays. Not only would this be the simplest conception that we can at present frame, since it would only call for further extension of the spectrum, but it would also keep X rays within the limits of electro-magnetic waves and in the immediate province of electricians."

A communication from Wilbur M. Stine and included in the published record told of some of the techniques used in extending the life of the tubes:

"After a time a period of decline sets in. The vacuum becomes extremely high, the fluorescence is scarcely perceptible, and the ray is weakly emitted, but its penetrating power has become so great that even the bony skeleton of the body becomes quite transparent. It is now customary at this stage to heat the tube with the flame of an alcohol lamp. As some erroneous statements have been made in this connection, the phenomena will be treated in detail. When the flame is first applied to the tube it darkens, being doubtless short-circuited by the aqueous vapor condensed on its surface. From time to time occasional flashes occur in the tube, but at length, with surprising suddenness, the entire bulb fills with the usual glow accompanying a highly active state, and the ray is emitted with great power. If at this juncture, the heat is not very cautiously applied, the vacuum will be quickly lowered to the point of breaking-down; the impact plane will grow red hot, and the penetrating power of the ray is feeble. By deftly reversing the tube and manipulating the heating, the vacuum can be controlled within wide limits."

After adjournment of the meeting, a communication was received from Charles T. Rittenhouse‡ for inclusion in the *Transactions*. It included these opinions:

"Every endeavor should be made to coordinate the results of experiments with Roentgen rays with the generally accepted theories of light, rather than to propose new theories, concocted without mature deliberation, likely to be upset at any moment by the announcement of some new phenomenon. It seems to me that it would be preferable to withhold opinions regarding the exact nature of Roentgen rays until a sufficient number of facts have been collected to form a basis for the advancement of a new theory. . . . In conclusion it may be said that when it is considered that Roentgen rays most likely consist of vibrations of such small wavelengths as to be comparable with the distances between the molecules of the most dense substances, it can scarcely be expected that regular reflection will take place to any large extent, but that dense substances having a most highly polished surface will still be as rough to these rays as a badly polished surface to ordinary light. In other words, regular reflection and diffusion are relative terms only, so that a given surface subjected to one mode of vibration behaves entirely different when receiving vibrations of a higher or lower order."

No further material on the subject was recorded during the few remaining years of that century.

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‡ Editor, *Electrical World*, New York, N. Y.

Scientific Importance of X Rays

L. HENRY GARLAND

"Come, come, and sit you down; you shall not budge;
You go not, till I set you up a glass
Where you may see the inmost part of you."
(*Hamlet, act III, scene 4, lines 23–25*)

THE DISCERNING English dramatist wrote these amazingly prophetic lines some 300 years before a modest German physicist announced the discovery of a "new type of rays." Yet, had he known, Shakespeare hardly could have penned a more apt description of a fluoroscopic examination—aided, it is granted in this instance, by a mirror, in which the good Queen of Denmark might "see her inmost part." To continue the remarkable coincidence, the Queen, like many an apprehensive patient, replies to Hamlet:

"What wilt thou do? Thou wilt not murder me?"

And Polonius cries forth:

"What ho! help, help, help!"

Before the days of shockproof X-ray equipment, such a scene might have taken place in a radiologist's office; today it should be a rarity (unless Polonius were confronted with the statement for an unusually prolonged and complicated series of examinations).

In the half century which has elapsed since Roentgen's announcement there have been many developments in medical science which, at first glance, might seem to dwarf the tremendous importance of the discovery of X ray. These developments include the perfection of antitoxic sera, of remarkable antibiotic agents (the sulfa drugs, penicillin, and similar molds), of stored blood or blood derivatives, and finally of planned atomic disintegration. Yet, we believe it is safe to hazard the guess that in another 50 years we still shall look upon the X ray as one of the developments of major scientific import of all time, as well as one of the most valuable weapons for medical care. We shall look back and thank the pioneers in physics, electricity, radiology, and general medical pedagogy who made equipment practicable and who encouraged physicians to specialize in the field of X-ray diagnosis and treatment.

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A practicing radiologist outlines the scientific and medical importance of the X ray first noted 50 years ago by William Conrad Roentgen and summarizes, briefly, a physician's view of its value to science in general.

GENERAL CONSIDERATIONS

To appreciate the importance of X rays it is desirable that certain basic facts be kept in mind. These rays are penetrating radiations corresponding to light rays but having much shorter wave lengths. They may be used in a manner similar to light rays for the inspection of some materials and, by virtue of their peculiar properties, for the analysis of others. Gross inspection methods include simple roentgenography (or X-ray "photography") and roentgenoscopy (or X-ray fluoroscopy); detailed inspection methods include various other means such as microradiography, Roentgen-spectroscopy, Roentgen-diffraction, and so forth. In practice, X rays usually are generated by allowing a stream of high-speed electrons to impinge upon a metal target. They have wave lengths of from 10.0 to 0.01 angstroms, and affect a sensitized film in a manner similar to that of light rays. They also cause certain substances to fluoresce. The materials through which they pass are ionized and give rise to scattered X rays. Because of this ionization, the rays are of use in the treatment of certain medical conditions. X rays can be reflected, refracted, and polarized by special means (including the use of crystals).

The principal use of X rays lies in their ability to penetrate opaque objects. Such objects arrest the rays approximately in direct proportion to their densities. Substances of low atomic weight such as cotton, gauze, and aluminum, are traversed readily by the rays, while other substances such as bone and heavy metals are opaque, and cast a dense shadow on a sensitized film. Some materials are transparent to light rays but opaque to X rays (for example, a plate of lead glass).

In the radiographic examination of materials (both animate and inanimate) it is important to remember that the delineation of an object depends on its differing in density from its surroundings. Unless such difference exists, the outline of the object cannot be shown on ordinary roentgenograms. A simple example of this is the demonstrability of the heart in X rays of the chest. Surrounded as it is by air-filled lungs, the heart is readily visible in chest films. However, if nature had placed it in the middle of the liver, no distinct shadow would be cast as the liver is of approximately the same density.

Under ordinary circumstances, X rays are not directly visible and require a specially prepared surface for their detection (a fluoroscopic screen or sensitized film). We use the adjective "ordinary" because you actually can see X rays with a little training and practice. Unfortunately, if you look at them sufficiently long, you will lose your eyelashes, and probably your eyebrows, if not most of your hair. This is because of the destructive effect of large amounts of X rays on the hair follicles and other living tissues. However, it is safe to gaze at the rays for a few minutes, using a small beam (perhaps one-inch diameter). One must sit in total darkness for some 30 minutes before one can appreciate the faint fluorescence produced by the rays on the human retina; one is then able to see small lead objects placed between the X-ray tube and the human eye, and, if one has an opaque lens (cataract) or cornea, one can ascertain whether or not the optic nerve is intact. The method is used occasionally by radiologists, at the request of eye specialists, to assure that the patient has an intact retina and nerve before surgical procedures on the cornea or lens are performed. It is to be noted that the objects will seem upside down, since the focussing power of the human lens will be ineffective with X rays.

The action of X rays on photographic film is similar to that of light rays. Ordinary X-ray films are coated on both sides with a silver halide emulsion, especially sensitive to the violet range of the spectrum, because they are used mostly with double intensifying screens which glow with that color. These screens consist of thin pieces of cardboard coated with calcium tungstate and a protective transparent film. They are placed in a special bakelite or aluminum-fronted frame, and for satisfactory results must make perfect contact with the film. Special nonscreen films may be used for improved detail, but are from five to ten times slower than screen films. The modern film has a cellulose-acetate base (with no greater fire hazard than paper). The finished roentgenogram is a negative image and is studied in a flashed opal glass illuminator.

The fluoroscopic screen usually is made with zinc sulphide because it must carry an image to be viewed directly and this chemical fluoresces in the color range to which the eye is quite sensitive (yellow green). Roentgen's original screen was made of barium platinocyanide, which was much less efficient than the present type. All fluoroscopic screens must be covered with lead glass to protect the operator from exposure to X rays. The operator must "adapt" his eyes prior to examina-

tion by remaining in a darkened room for several minutes or by wearing special goggles before beginning the work.

A beam of X rays consists of electromagnetic radiations of various wave lengths. If of very short wave length they are of high penetrating power; if of very long wave length they may penetrate only a few millimeters of tissue. The quality of a beam of rays may be measured by various methods, the most convenient one in ordinary practice being the determination of their absorption by some material such as copper or aluminum. A spectrometer can be employed, but is too time-consuming and troublesome for routine use. The quality is expressed as the thickness of an absorber which reduces the intensity of a given beam to one half its initial value, and the resulting figure is known as the half-value layer for that beam. For low-voltage rays (up to 20 kv) cellophane may be used as the absorber; between 20 and 120 kv, aluminum; between 120 and 400 kv, copper; and for more than 400 kv, lead or tin. A refinement of the method is to record a second half-value layer, the ratio of the second to the first being used as an index of homogeneity. It is to be noted that the expression half-value layer is only part of the description of the quality of a given beam; for scientific purposes one also must specify the nature of the target material, the tube wall, and the generator wave form.

The quantity of X rays in a given beam at a given point may be measured by recording the ionization in a fixed volume of air or gas at that point. The "roentgen" is the unit of X-ray quantity and is defined as "that quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit of electricity of either sign." The mass of one cubic centimeter of air at 0 centigrade and 760 millimeters of mercury is 0.001293 gram; in biological work, one roentgen equals 83 ergs per gram of tissue. The rays usually are measured by an electroscope attached to a small thimble chamber composed of a special light plastic material. It is of interest to note that the almost universally used instrument at the present time is a "condenser Roentgen meter" designed and manufactured in Cleveland, Ohio.

X RAYS IN SCIENCE

The importance of X rays to science in general is so great that a volume would be necessary to describe it. However, a few of the more interesting applications of X rays will be mentioned in this article and an attempt made to give a clue to their true value. For the sake of brevity the sciences will be grouped into a few general categories.

Anatomy and Physiology. The importance of X rays to anatomy, comparative anatomy, paleontology, and associated sciences is now well appreciated. However, it is not realized generally that the modern method of teaching anatomy to medical and other students involves the use of roentgenological demonstration of the skeleton and its various associated soft parts, both in the cadaver and in the living subject. In this manner the appearance and behavior of bony and other structures in the living is demonstrated in a way never before possible. The study of the skeletal development in vertebrate embryos is facilitated enormously by Roentgen methods. The anatomy of small and large animals is revealed in zoological work. The status and often the diseases of mummies may be determined without opening the wrappings or even the sarcophagi. Genetics has been furthered by studying the behavior of many species, notably drosophila melanogaster (the common fruit fly) following exposure to specific quantities of X rays (with the production of subsequent mutations of certain types).

Physiology is greatly indebted to roentgenologic methods, notably in connection with the study of the alimentary tract, the circulation of the blood, and the functioning of moving parts, especially joints. X-ray "movies" as well as fluoroscopy and "still" films have been used extensively in this field. As an example of their value in one small department the X-ray (kymographic) determination of cardiac output can be cited.[3]

An X-ray film is made of the subject's chest, in the erect position, at a measured distance (say five or six feet), using a lead grid between the patient and the film. The exposure takes about two seconds' time and the film is moved slowly downwards a distance of 12 millimeters during the exposure. When the film is dried, the outline of the heart appears as a serrated border, the "peaks" representing the shadow in maximum expansion and the "valleys" in maximum contraction. The peaks are joined by one line, the valleys by another. The rest of the heart shadow is completed as shown in Figure 1. The area in these two phases then is measured with a planimeter and the figures corrected for distortion. The corrected figures then are converted into volumes according to a table established from experimental and cadaver work. The difference in volume between expansion and contraction gives the output per beat. In many normal subjects the average stroke output per ventricle is 60 cubic centimeters; a person with a rapid pulse tends to have a smaller and one with a slow pulse a correspondingly larger ouput. Therefore, it is more informative to speak of the output per minute than the output per stroke; this in turn varies with body size, which may be expressed fairly simply in terms of total body surface. The number of liters of blood pumped per minute per square meter of body surface is termed the cardiac index. This index thus may be found by using this particular X-ray method. (Needless to say, there are other methods of determining this index, but the roentgenkymographic one is a simple and reliable one when correctly used.)

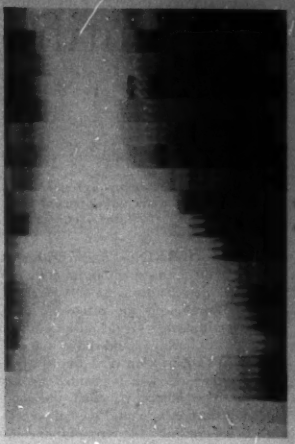

Figure 1. Roentgenkymogram of the heart of an adult male, exposure time two seconds

Three contractions of the heart are visible in each of the frames with the tip or peak of each wave representing maximum expansion and the base or valley maximum contraction of the heart (diastole and systole, respectively). The contractions are of normal amplitude and shape

Our knowledge of the functions and behavior of the alimentary tract in health and disease is largely dependent on the use of Roentgen methods of examination. Some of the earliest investigators in this field have been American physiologists who did their original work on cats (to whom they fed bismuth in milk, and so forth). Food also may be used, provided it is opaque to the rays. On an early morning walk near San Francisco several years ago, I came across a plump horned toad. Having a little time to spare that day, I brought the toad into my fluoroscopic room and placed it on the table. I then captured a common house fly and dusted it with barium sulphate. After setting the tasty meal beside the toad I turned on the X rays and watched the inevitable and fascinating sequence of events. The barium cast just as good a shadow in the toad's stomach as it does in the human, and the progress of the meal could be studied easily.

Physics and Chemistry. The use of X rays in the sciences of physics and chemistry and all their innumerable ramifications is an ever-expanding chapter in X-ray history. The gross analysis of many materials may be performed in part

by roentgenoscopy or roentgenography, and the detailed analysis by methods such as Roentgen diffraction, crystallography, or electron microscopy. The diffraction method of measuring small objects is well established. The principle depends on the fact that a beam of light or X rays which has traversed a collection of small objects is seen surrounded by a series of rings or diffraction spectra, from the diameter or pattern of which the size of the object can be calculated. A familiar example is the ring visible around lights on a misty night, the diameter of which is determined by the mean diameter of the mist particles. The interpretation of X-ray diffraction patterns in terms of the ultimate structure of crystals and solids has its foundations in crystallography. By such methods it is found that rubbers, plastics, and fibers, although superficially different, are intrinsically similar materials. X-ray studies also have assisted greatly in analyzing the structure of the higher polymers. The essential features of such diffraction apparatus are:

1. A source of X rays.

2. A device to limit the rays to a beam of minimum divergence.

3. A holder to support the test specimen in the beam.

4. A means for recording the X rays diffracted from the sample of critical angles (determined by the crystal structure of the samples).

A recent issue of *Electrical Engineering* included a description of a method of X-ray analysis of unknown chemical substances by employing a new photoelectric Roentgen intensimeter.[1] The meter is said to be so delicate that if the X rays are passed through a pile of 100 sheets of paper, the difference in absorption caused by adding or subtracting a single sheet can be recorded.

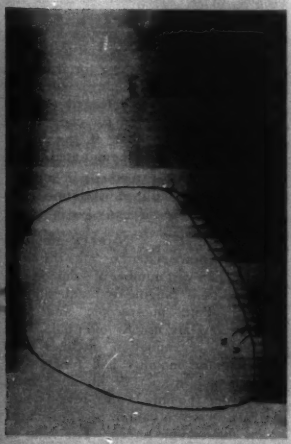

Figure 2. Same case as shown in Figure 1 illustrating method of tracing the outline of the heart shadow in contraction (S) and expansion (D)

In this way the output of the heart is ascertained

As a direct result of investigations in physics and chemistry there are numerous industrial and commercial X-ray developments which include the following:

1. The examination of various complicated appliances, such as radio tubes, without the necessity of breaking open the tubes.

2. The examination of castings and welds.

3. The examination of packages and personnel for concealed material.

4. The examination of edible materials for defects or impurities (such as candy bars and oranges).

5. The behavior of solids and liquids under projectile bombardment (such as high-speed roentgenography of bullets).

The roentgenographic examination of metal parts in connection with the airplane industry is said to have used up more film per month during the last few months of the recent war than was used in all medical procedures in the United States during the same period. The importance of skilled interpretation of these roentgenograms and of adequate protection for the employees operating the X-ray equipment obviously is great.

Since the early days of X-ray development, packages, clothing, and even personnel have been inspected for contraband and other illegally possessed materials. Packages and similar objects may be inspected without harm, provided they do not contain unprocessed film or other sensitized material. Individuals may be examined only under stringent conditions as exposure of large amounts of the body to X rays, especially if repeated, is fraught with ultimate danger to the individual; possibly resulting later in skin damage, anemia, or infertility.

It is to be recollected that metals and other materials may be radiographed either with X rays or radium rays. It is therefore appropriate to consider a few aspects of radioactive substances as many of them have properties analogous to those of X rays. Radium rays are of three general types:

1. Alpha rays, which are positively charged particles of very low penetrating power, being stopped by a sheet of ordinary paper.

2. Beta rays, which are negative electrons, of moderate penetrating power, stopped by a thin metal filter (two millimeters of brass or 0.5 millimeter platinum or their equivalent).

3. Gamma rays, which are electromagnetic radiations (photons) of considerable penetrating power, the hardest ones traversing several centimeters of lead.

Because of their different charges, these three types of rays can be separated in a magnetic field. The alpha rays are deflected slightly in one direction, the beta more strongly in the opposite direction, and the gamma not at all. Radium disintegrates slowly, its half period being 1,590 years. For medical purposes it usually is kept in small containers in the form of a radium salt. Many of these containers can be placed together and the group then used like an X-ray tube.

Since the work of Rutherford, in 1919, we have been able to produce artificially radioactive substances. One method of doing this is to use the cyclotron, by means of which the nuclei of atoms are transformed into new unstable substances. High-speed protons, deuterons, and neutrons have been used to transform most elements. The resultant radiations are of many types (alpha, beta, gamma, neutron, and positron). Many biologically useful radio elements are produced by deuteron bombardment and include radiophosphorus, radiosodium, radioiron, radioiodine, and radiostrontium. These substances can be administered to patients and their exact method of localization and storage in the human body studied by means of Geiger counters and similar apparatus. In this manner the metabolism of certain living tissues, in both health and disease, can be studied more completely than ever before. For example, totally new information concerning the need for and method of use of iron in the human body, in conditions like anemia, has been obtained.

An indirect development of high-voltage tubes in physics is the electron microscope which permits much higher magnifications of minute objects than are feasible with optical microscopes. With this instrument the image of the object is viewed either on a fluorescent screen or is recorded on a photographic film. Recent developments include modifications by which the instrument may be used either as a diffraction camera or a microscope. Stereoscopic electron micrographs can be made. The usual electron microscope operates at about 60 kv, but there is a small table model operating at 30 kv. The structure and behavior of viruses has been studied for the first time, and the detailed structure of bacteria has been revealed. Chromosomes, the tiny rod-like particles that bear the major responsibility for inherited characteristics, may be examined, and by means of ingenious methods the actual location of certain specific genes in a number of chromosomes has been determined.

Biology. X rays have been used in most of the various biological sciences, notably in botany and zoology. The architecture of many forms of plant life have been studied by macro as well as microradiography. Mutations have been produced by bombardment of seedlings and

rootlings with X ray, and new hybrids successfully developed. In fact, one physician insists that a special type of begonia he grows is a direct result of irradiation of a former plant. He gives no credit to Mendel's cosmic ray but, unfortunately, I am not sufficiently familiar with botany to know whether or not he is correct.

In zoology, several forms of animal life have been studied with X rays. With the larger type of animal one naturally has to make segmental studies. About a generation ago an ailing elephant at the London zoo was subjected to X-ray examination. The tired pachyderm lay on her side and had her torso marked with chalk into a series of rectangles, each a little less than 14 by 17 inches in size. These then were numbered in sequence and a series of roentgenograms made. We cannot vouch for the quality of the films made through the thicker parts, but those of the extremities which we saw were quite good. Race horses, greyhounds, parrots, and other domestic pets frequently are subjected to examination in connection with injuries, foreign bodies, and certain diseases. Before the development of shockproof apparatus, cats were particularly difficult to X ray as they have a strong dislike for the hair-raising qualities of the corona from exposed high-voltage wires.

Miscellaneous. One of the lesser known but more valuable uses of X rays is in connection with art. Many pigments contain lead and other radiopaque salts and the roentgenogram of a canvas often reveals shadows different from those on the visible painting. Areas of overpainting, alterations, and erasures can be detected. The authenticity of some old masters has been proved and of others disproved by such means. A recent refinement includes sectional radiography of the canvas in which, by keeping the tube and film in motion, a very fine layer of the painting can be registered to the exclusion of other layers.

X RAYS IN MEDICINE

The importance of roentgenologic methods in medicine, dentistry, and allied sciences is increasing continually. They permit the examination of parts of the body hitherto inaccessible to study and the detection of disease at a stage when it may be cured readily. They extend the physician's eye to an incalculable distance. They are also of use in the prevention of disease and in its treatment. (A small precancerous skin nodule, keratosis, may be cured before it develops into a malignancy; established, localized, accessible cancer can be destroyed.) Our knowledge of many diseases such as stomach ulcer, lung tuberculosis, and bone cancer has been entirely revolutionized and reoriented since the discovery of X rays. They have provided an impetus to investigation and research in preventive medicine such as no other weapon ever placed at the disposal of the doctor.

Table I. The Electromagnetic Spectrum

Type of Radiation	Range of Wave Lengths	Range of Frequencies
Electrical waves	1,000,000 to 20 kilometers	10^{-1} to 10^{4}
Radio waves	20 to 0.01 meters	10^{8} to 10^{11}
Infrared rays	120,000 to 7,700 angstroms*	10^{11} to 10^{14}
Visible rays	7,700 to 3,900 angstroms	
Ultraviolet rays	3,900 to 1,800 angstroms	
X rays	10 to 0.01 angstroms	
Gamma rays	0.1 to 0.02 angstroms	
Cosmic rays	0.00001 + angstrom	

* 1 angstrom = 10^{-8} centimeters; 100,000,000 angstroms = 1 centimeter.

One might arrange this section according to the various medical specialities, but I think it will be of more interest to nonmedical readers to consider the importance of the rays according to each of the various systems of the human body. However, it is timely at this point to acknowledge the debt of roentgenology to members of the specialties outside of its own field, physicians who have contributed greatly to the refinements of many techniques in diagnosis as well as treatment. The reader should know that there are now "national qualifying boards for specialists." These boards examine eligible graduate physicians and certify those who pass successfully. At the present time there are boards in the following branches of medicine:

1. Anaesthesiology.
2. Dermatology and syphilology.
3. Internal medicine.
4. Neurological surgery.
5. Obstetrics and gynecology.
6. Ophthalmology.
7. Orthopedic surgery.
8. Otolaryngology.
9. Pathology.
10. Pediatrics.
11. Plastic surgery.
12. Psychiatry and neurology.
13. Radiology.
14. Surgery.
15. Neurology.

X-ray diagnostic methods involve first and foremost intelligent use: one case may be diagnosed quickest without X rays at all; the next may need only fluoroscopy; the third, fluoroscopy, roentgenograms, and special-section techniques; the fourth may require repeated roentgenograms. Only a trained physician knows the correct answer to these questions: only a trained physician can be economic in the exposure of your tissues to a radiation known to be noxious. The wise layman selects his physician–radiologist according to his experience or ability, and not according to the newness or extent of his equipment. In assessing the value of a roentgenogram it is important to remember that it is just a shadowgraph and not a true photograph and as such is subject to erroneous interpretation. Furthermore, the roentgenogram is a projection on a flat surface of everything on every plane between the X-ray tube and the film. Thus it is desirable that the interpreter familiarize himself with the projected appearance of normal structures of various shapes. Multiple views, preferably at right angles, usually are essential; stereoscopic roentgenograms frequently are necessary. The examination of moving parts such as the stomach, heart, or diaphragm frequently requires fluoroscopy as well as multiple films.

There are many shadows in roentgenograms of healthy persons which cause errors in interpetation. These include the normal epiphyseal or growth line in bones (often mistaken for a fracture), the overlapping of a bony margin, or the slender canal of the artery to the bone. The existence of a congenital fissure or cleft also may be mistaken for a fracture. Calcium deposits are fairly common in various tissues; they are normal findings in rib cartilages, laryngeal cartilages, and certain other areas, but occasionally they are mistaken for tuberculous lesions, foreign bodies, and so on. This is one of the reasons why a consultant roentgenologist may require stereoscopic or other additional projections even though you present yourself with a perfectly good film made elsewhere only a few days before. A small wart on the back may be projected on a film in a manner identical with that of a kidney stone or gall stone. Visual examination of the undressed patient or stereoscopic projections should prevent an error being made. In general, it is advisable for persons to be undressed when having X rays taken, since objects such as ear-rings have been mistaken for misplaced tooth-root fragments, buttons for gallstones, and the edge of folded clothing for fractures. Faulty darkroom technique sometimes results in undeveloped or fogged areas of films which can suggest (in chest films) pneumonia or (in films of the limbs) diseased bone, even to the initiated.

The use of X-ray methods in medical diagnosis may be outlined in relation to the various systems of the body.

Alimentary System. X-ray examination of the alimentary system permits the early diagnosis of a vast number of common disease conditions, ranging from adhesions to volvulus. Both fluoroscopic and film examinations are usually essential. The fluoroscopic examination discloses facts regarding the mobility and function of organs which cannot be obtained from films alone; the films in turn reveal detail of structure which cannot be appreciated on the fluoroscopic screen. The value of either method depends on the skill, patience, and experience of the examiner. When it is a question of a condition such as early stomach cancer, the examination may have to be repeated two or three times before a reliable opinion can be

rendered. For the upper part of the system (the gullet, stomach, and small intestine) it is necessary for the patient to come fasting. He is given a drink of barium sulphate suspended in water and the appearance of these portions of the tract is studied under the fluoroscope. Patients often complain at the chalky taste of the bariumized water. The reason that flavoring agents are not used is that in some persons they stimulate large amounts of gastric secretion which dilutes the test meal undesirably. In the early days of roentgenology the barium or bismuth used to be given in flavored preparations. However, if these contained much milk or cream, stomach emptying would be (physiologically) delayed. If they contained much sugar, stomach emptying would be hastened. These conditions often resulted in erroneous conclusions as to the presence of gastric stasis. In the average case four ounces of barium sulphate (by weight) are given in about eight ounces of water. This eventually mixes with the other contents of the intestinal tract and does not require laxation for its natural ejection.

The lower portion of the alimentary system normally is examined by barium enema. Sixteen ounces of barium sulphate are suspended in two quarts of warm water, with the addition of some medium such as acacia solution to maintain suspension during the procedure. After fluoroscopic and roentgenographic examinations the patient evacuates the suspension.

Conditions diagnosable by X ray include varicose veins in the gullet, ulcers, and tumors in the stomach or duodenum. Before the days of X ray, duodenal ulcer was considered a rarity; a person with severe and prolonged indigestion was usually diagnosed stomach ulcer. Since the development of Roentgen methods it has been found that most of such cases are actually due to duodenal ulcer, the latter being over 20 times as common as gastric ulcer. This was one of numerous revolutionary findings during the first two decades of this century.

Gastric cancer is one of the most common and serious malignant tumors in man; unfortunately it tends to be asymptomatic in its early stages and therefore its presence is not manifested until it is pretty well advanced. Persistent disturbance of digestion in men over 40 renders X-ray examination of the stomach advisable. The growth shows as a small intrusion on the barium shadow or as a small zone of immobility of the stomach wall.

The normal appendix usually is visible at some time during X-ray examination of the intestinal tract. It may be seen to fill and empty but if it does remain filled for some days this finding alone is not of grave importance. The X-ray evidence of acute disease in the appendix consists of marked local tenderness, absence of or incomplete filling, delay in the passage of the barium in the adjacent terminal inches of small bowel, and, occasionally, a local inflammatory mass. However, the diagnosis of acute appendicitis is more reliable when made by methods other than radiological ones.

X-ray examination is invaluable in the study and elucidation of the various diseases of the colon.

The liver and spleen are normally visible in most abdominal roentgenograms. Their visibility may be enhanced by intravenous injection of thorium dioxide sol (thorotrast), a drug which has the property of depositing itself in the small cells lining certain portions of the liver and spleen (the reticuloendothelial cells). The thorium is opaque and aids in the diagnosis of certain tumorous and cystic diseases of these organs. After seven years, thorium degenerates into a mildly radioactive product, but the amount necessary for ordinary examination has been shown to be so small that no harmful late radioactive changes develop. Another area of the alimentary tract which may be examined by selective methods is the gall bladder. If you ingest a suitable iodine preparation, the material will be excreted in your bile and will be concentrated in the gall bladder; provided the duct between the liver and gall bladder is not blocked and you remain fasting. This test is a valuable method for the detection of nonopaque cholesterin stones in the gall bladder; indeed, it is the only method by which such may be diagnosed preoperatively.

Cardio-vascular System. The accurate determination of heart size in the living human being can be made only by roentgenological methods. It is to be noted, in passing, that this is not always a very important factor, since cardiac function rather than size governs most healthy lives, and function can be assessed by many means much more accurate than roentgenologic ones. However, the problem of heart size does come up in some individuals and Roentgen methods are then invaluable. Correction should always be made for the amount of magnification present, the phase of respiration in which the patient happens to be during the exposure, and similar items. As in the case of the alimentary tract, complete examination of the cardiovascular system involves both fluoroscopy and roentgenography. In recent years the use of opaque substances has permitted the outlining of the individual heart chambers in the roentgenogram and the study of the circulation in a manner one could scarcely have even dreamed of 50 years ago. Besides giving information concerning the size, shape, position, and mobility of the heart, Roentgen methods also may disclose the presence or absence of coronary disease and its sequelae. Records of the beating heart may be obtained on a single film by means of kymographic apparatus and deductions as to the presence of localized areas of heart-muscle disease deducted therefrom. The condition of the arteries and veins in the extremities can be studied by means of both plain films and films made with contrast media and the presence of varicose veins in the deep venous circulation of the leg can be detected and unnecessary operations avoided.

Figure 3. Left wrist of adult male showing faint fracture line in one of the small bones (the scaphoid)

Fracture is indicated by arrow

Central Nervous System. Medical advances in the diagnosis and treatment of diseases of the brain, spinal cord, and peripheral nerves is one of the most interesting chapters in modern science. The normal brain casts no distinguishing shadow in the routine roentgenogram. However, by very simple methods, its outlines can be revealed. This consists of performing a spinal puncture (in the lower portion of the back), withdrawing from 75 to 150 cubic centimeters of cerebrospinal fluid, and injecting in its place a corresponding amount of air. Upon placement of the patient in an erect position this gas will ascend into the cerebrospinal fluid pathways around, between, and in the various lobes of the brain. Several plain or stereoscopic roentgenograms then are made from various angles, with the patient both erect and horizontal. The air absorbs during the next few days and is replaced by normal fluid. By this method various types of brain injury, brain disease, and tumors may be detected. Considerable experience is desirable in interpreting these pneumo-encephalograms.

The spinal cord may be studied by similar methods, or by the injection of radio-opaque contrast media into various portions of the spinal canal. The media most commonly used at the present time are preparations containing iodine (iodized poppy-seed oil and ethyl iodophenylundecylate). About three cubic centimeters of the opaque oil are injected in the lower lumbar area and the patient is fluoroscoped

Oval area of pallor surrounded by brown pigmentation is the effect of a second-degree burn suffered some months before when the patient underwent X-ray examination of his stomach by an untrained worker

Figure 4. Localized bleaching of the skin of the lower back of an adult male as a result of excessive Roentgen irradiation (healed X-ray burn)

on a special table. By tilting the body up and down, the lake of opaque oil can be made to traverse the spinal canal. Indentations and certain other alterations of its shadow will disclose the presence of ruptured disks, tumors, and so forth.

Genito-urinary System. It is now possible to examine the outlines of virtually every portion of the genito-urinary system. One can determine the function of each kidney following intravenous injection of an iodine salt selectively excreted by the kidneys. The seminal vesicles and ducts may be outlined by contrast media. Similarly, the cavity of the uterus and the slender canals of the fallopian tubes can be shown. In this manner an extraordinary variety of conditions, normal as well as abnormal, may be detected. The number, size, and approximate age of infants in utero may be told. The exact alterations in the shape of the fetal bones during the actual process of birth have been studied by serial roentgenograms. The remarkable molding and elongation of the fetal skull have been shown, as well as the disposition of the fetal limbs and placenta. The latter has been studied by arteriographic injection of opaque media and valuable information as to the uniovular or multiovular nature of twins ascertained. Abnormal gestations have been diagnosed correctly in time to save the mother an unnecessarily prolonged pregnancy or labor. These cases are some of the most tragic incidents that a radiologist encounters. The normal fetal skeleton does not contain sufficient calcium to cast a clear shadow in routine roentgenograms before a gestation period of 12 weeks. Within increasing accuracy after that time the fetal parts may be shown. Attempts have been made to determine the sex of the fetus by X-ray methods, but no practical method has yet been found. Extensive studies have been made on the influence of the shape as well as the size of the female pelvis on spontaneous delivery. Female pelves are classified into four general types, based on their shape. By careful Roentgen examination, the probability of easy or difficult labor can be prognosed with considerable accuracy in selected cases.

Osseous System (Bones and Joints). The first use of X-rays was in the examination of cases of suspected fracture. From that day its uses have been extended to include the study of bone growth, bone tumors, joints, tendons, bursae, and adjacent structures. In the correct diagnosis of all bone conditions, and in the treatment of many of them, X rays are essential.

The detection of a gross fracture in an ordinary roentgenogram is a simple matter; the detection of fine or fissure fractures is often extremely difficult. An important example of this is in injuries involving the wrist, probably the most commonly injured area in the body (see Figure 3). One type of "sprain injury" results in fracture of the scaphoid or navicular bone, a small bone in the wrist joint. This bone has a very critical blood supply. If injured, healing requires immediate and complete immobilization for many weeks. Fractures of this bone are often difficult to detect except in films of the highest technical quality; three or four views may be necessary before the crack can be confirmed or excluded. If overlooked, and the wrist is not immobilized, most of these cases result in nonunion and chronic arthritis in the wrist joint, a serious source of disablement in laborers. Attempts have been made to restore the function of the joint by removing the two broken pieces of scaphoid and replacing them with a synthetic bone (made of a biologically tolerable metal such as vitallium) but these results have not been conspicuously successful. The only method of assuring safety is early X-ray diagnosis and complete immobilization.

Fractures of the ribs are quite common and usually unimportant injuries and the vast majority of them heal without any particular treatment. However, compensation and legal considerations often require an answer as to whether or not a fracture is present in a given case of alleged chest injury. In at least ten per cent of actual fracture cases, the fracture line is not immediately demonstrable by ordinary X-ray methods. It is concealed by its obliquity or by overlapping parts. Therefore, your physician may tell you in such a case that there is "no X-ray evidence of fracture" rather than "there is no fracture." If it should be of legal importance to confirm a suspected fracture in such a case, re-examination at the end of four-weeks time usually will provide the answer. By that time a little "fuzz" of new bone will be present in the fracture site and will be visible in the roentgenograms.

Roentgen methods are also invaluable in the detection of various types of bone disease due to infection, tumor, and so forth. However, the shadows cast often are not characteristic of one particular infection. For example, a bone that has been disused for several weeks (perhaps in the foot, when a patient is wearing an extensive plaster splint for fracture of the upper leg) may cast a shadow identical with that of one extensively diseased. Therefore, it is necessary for the roentgenologist to have some of the clinical facts or history of a given case before rendering an interpretation of a film. The film is not misleading; our deductions, in the absence of clinical data, may be misleading.

Some diseases cause fairly characteristic changes in bone, but these are in the minority. The more experience the observer has the more he realizes that a host of different conditions can produce identical pathological and, therefore, identical radiological changes. A good example of this is leprosy. Many years ago an author reported "characteristic" atrophy of the terminal phalanges as a fairly early sign of this disease. On studying cases of nerve disease of other types, and of obliterative or spastic vascular diseases of various types, it was found that quite identical changes occurred in many of them. Phosphorus poisoning causes changes in the jaw bone similar to those of infection and of radium poisoning. Thus, it is important to maintain reserve in accepting reports of new or "characteristic" findings in disease.

One interesting finding in roentgenograms of children's extremities is that seen in lead poisoning. Children who have licked the paint off of their toys or pens sometimes develop signs of joint disease or leg weakness. If they have been following this dietary indiscretion for some time, the growing ends of long bones will show dense lines due to actual deposit of lead salts therein.

The roentgenologist is required to have a general knowledge of the development, anatomy, and pathology of the teeth. Satisfactory examination of the teeth requires careful technique and even more careful interpretation. Without the latter, early abscesses at the roots of the teeth, early areas of caries or decay in the crowns, and similar processes may be overlooked.

The value of a consultant specialist is almost nowhere better seen that in certain cases of dental radiography. The dentist or family doctor is apt to look at such films with his thoughts concentrated purely on the dental structures and innocently may neglect a malignant growth in the adjacent bony mandible, a lesion which an expert in the field of X-ray interpretation would be apt to detect readily. It is not suggested that ability in such interpretation is confined exclusively to the roentgenologist. Any person, professional or otherwise, can learn how to interpret films of certain parts of the body after a fairly short period of training. However, the human tendency is to concentrate on the matters in which one is most interested and to overlook other data, even though such are quite apparent on retrospect.

Normal joint cartilage casts no distinguishing shadow in roentgenograms so routine Roentgen methods are not of much value in the early diagnosis of many types of joint disease. However, "soft-tissue" films of joints, and films made following intra-articular injection of air do provide valuable diagnostic information in many cases. Roentgenograms are of considerable value in the differential diagnosis of established cases of joint disease (chronic rheumatism, gout, specific infection). Bleeding in and about joint areas, such as occurs in hemophiliacs, presents fairly characteristic changes.

Respiratory System. If roentgenology had made no other contribution to medicine than the ability to study the shadows cast by the lungs in living individuals it would have performed a tremendous boon. But before considering this portion of the system, let us commence at the upper portion of the respiratory tract, namely the nose and nasal accessory sinuses. The cartilages, bones, and even the skin of the nose can be radiographed with simplicity, and various injuries and other conditions accurately diagnosed. The nasal accessory sinuses, nasal passages, and adjacent areas can be recorded and various conditions ranging from sinusitis to cancer detected. The air passages leading from the nose to the lungs can be portrayed and the true and false vocal cords may be studied both fluoroscopically and radiographically. A special technique known as body-section roentgenography (laminography or omography) permits the obtaining of films of such areas as the cords relatively free from under- or overlying shadows. In this method the tube and film are moved synchronously but in opposite directions about a fulcrum, the location of which depends on the height above the X-ray table of the area to be studied.

All types and varieties of diseases of the lungs and pleura are amenable to X-ray diagnosis, and many require such examination for their elucidation. Communicable diseases such as active lung tuberculosis provide an excellent example. In recent years the training of increased numbers of physicians in radiology plus the development of special X-ray apparatus has permitted mass surveys of hundreds of thousands of individuals. The best method involves the use of standard (14- by 17-inch) films. A slightly less expensive and currently popular method is the photofluorographic one, in which the fluoroscopic image is photographed on small or roll film (35-millimeter, 70-millimeter or 100-millimeter widths, depending on the type of equipment). The film comes in rolls of from 35 to 100 frames, permitting a like number of exposures. Some of the newer units have built-in photoelectric cells by which the X-ray exposures are timed automatically. This strip film is processed in special developer, then dried and viewed either in a magnifying transilluminator or by means of a projection unit. The detail in the films is naturally not as great as in the conventional 14- by 17-inch film but it is sufficiently good to permit screening of lungs for significant lesions. The prime object in the method is to detect cases of open pulmonary tuberculosis, that is, patients with cavities or other lesions from which they cough bacilli and so innocently infect their fellow citizens. Miniature films permit the detection of most such lesions. About one per cent of apparently healthy adults are found to have some significant lung condition on such surveys, but fortunately only one in 400 has evidence of "open" disease.

The X-ray unit has not made the stethoscope obsolete but it has given the physician a weapon with which he may detect numerous diseases of the chest at a stage long before they could otherwise be discovered. In this manner they have been a major factor in saving countless lives and in preventing much advanced disease.

LOCALIZATION OF FOREIGN BODIES

X rays are essential for the detection and accurate localization of most foreign bodies in the tissues. These bodies may be divided into two general types, nonopaque to the X rays and opaque. Surprising as it seems, nonopaque foreign bodies frequently may be localized, with considerable accuracy, by careful examination. For example, a peanut lodged in one of the bronchial tubes will itself cast no shadow, however, it will produce partial or complete obstruction of the bronchus. As a result the involved lobe of the lung will show either persistent distention with air on expiration, or gradual collapse. Nonopaque foreign bodies in the alimentary tract often may be located by giving the patient small barium-soaked cotton pledgets or swallows of barium cream. Nonopaque foreign bodies in other parts of the body sometimes are located by injecting radiopaque liquids into draining sinus tracts.

Opaque foreign bodies, common in war time, may be found and localized by various methods. The simplest is by roentgenoscopic and roentgenographic examination in two planes at right angles to each other. Other methods include parallax and triangulation. The detection and localization of small metallic bodies in the eye may be performed with the aid of special apparatus. That most generally employed involves examining the patient's eye in accurate relationship to two fixed objects placed at a known distance from the cornea. The data obtained from two films made at different angles are transferred to a special ruled chart, and the position of the body indicated in three different planes with an accuracy of less than one millimeter.

Protection against unnecessary or excessive exposure to X or radium rays is of the utmost importance for patient, operating personnel, and radiologist. Protection against excessive exposure from the direct beam is now well-established in responsible offices and departments by methods which include careful calibration of the apparatus, adequate distance between tube and patient's skin, use of lead-protected shockproof tubes, suitable diaphragms, and filters.

Protection against radiation scattered from the patient or the X-ray table is often more difficult but unfortunately, sometimes is overlooked. The best way to achieve this protection is to use as small a beam as possible in examining patients, to work as expeditiously as is consistent with thoroughness, and to stay at the maximum distance or behind the safest barrier available. Protective barriers usually are made of lead or concrete. If workers are not safeguarded properly they may develop injury to the blood or reproductive system with consequent dangers of anemia, leukemia, or sterility. The tolerance dose is the total X-ray energy that a person may receive continuously without suffering damage to the blood or reproductive organs. For most workers it is set at 0.2 roentgen per day (a dosage rate not exceeding 10^{-4} per second). Detailed rules for protection are available in the National Bureau of Standards Handbooks 20 (*X-Ray Protection*) and 23 (*Radium protection*).

X RAYS IN TREATMENT

X rays are of considerable significance in the treatment of a large number of diseases, ranging from simple infections such as ringworm of the scalp to serious processes such as cancer. The physician performing Roentgen therapy must strive to be as careful in the calibration and handling of his apparatus as a physicist, and as accurate in the application of his rays as a surgeon is when applying his knife. The therapist has at his disposal a wide variety of equipment supplying low-voltage beams for superficial treatment (40 to 100 kv), intermediate voltage for more deeply seated lesions (120 to 150 kv), high voltage for deep-seated lesions (180 to 220 kv) and, finally, extra-high voltage

for a few selected conditions or for biological research (400 to 1,000 kv). He must select a filter suited to the procedure desired, varying from less than one millimeter aluminum up to as much as five millimeters of copper. He calculates his dose in roentgens, and delivers small doses to most inflammatory or benign conditions, and very high doses to certain localized malignant lesions. A small dose ranges from 10 to 100 roentgens and may need to be repeated at intervals for weeks or even months. For example, generalized acne vulgaris may require weekly doses of 100 roentgens for three months. On the other hand a small localized cancer may require 6,000 roentgens delivered either at one session or, depending on the amount of associated infection and similar complications, in several sessions. The essential effect of X and gamma rays on the tissues is a destructive one. Cancer cells are slightly more sensitive to such radiations than are normal cells, and for this reason it is possible to destroy some cancers without permanent injury to the normal surrounding tissues.

The following is a partial list of conditions in which X or gamma rays are of value: Inflammatory diseases of the skin and adjacent tissues; certain thickenings of the skin (plantar warts, keratoses); disturbed function of certain glands such as salivary and thyroid (hyperthyroidism); many benign and malignant tumor conditions.

Just as the mere possession of a knife does not make you a surgeon, so the possession of X-ray apparatus or radium does not make you a radiation therapist. The safe and efficient application of radiation methods in disease requires as much skill and even more training than many types of surgery. It also requires recognition of the fact that there are many conditions far better treated by nonradiological methods and a few which actually are rendered worse by Roentgen treatment.

The rays may be applied to human tissues by a variety of methods including external application of the beam, internal (intracavitary) application, interstitial application (that is, direct insertion of radium or radon seeds into the tissues), and various combinations of these methods, all designed to deliver the involved tissues a specific planned radiation dose.

FUTURE DEVELOPMENTS

The world has seen tremendous advances in the X-ray field during the past 50 years but there still are numerous developments, both in apparatus and technique, to which physicists and physicians are looking forward. These include the following:

1. More efficient recording media, including improved film emulsions, processing equipment, and fluorescent screens.

2. Improved simplified exposure meters and automatic timers.

3. Finer focal-spot diagnostic tubes.

4. Greatly improved fluoroscopes, perhaps an electron fluoroscope, and, as a result, better safer X-ray motion pictures.

5. More widespread use of X rays in teaching and in preventive medicine (including the installation of X-ray units in morgues to aid in research and routine autopsy work).

6. Improved methods of calculating the size and depth of tumors, so that radiation beams may be still more accurately aimed.

7. Improved selection of patients for both diagnosis and treatment (to reduce unnecessary expense and unnecessary exposure of human tissues—especially the reproductive organs—to X or gamma rays).

8. Finally, and most important of all, the training of more and better radiologists; medical physicians specializing in X-ray diagnosis and treatment.

The value of X rays to science in general and to medicine in particular is immense and ever-increasing. They have provided us with a weapon by which we may search out the structure of matter, as well as the hidden components of the body. The diagnosis of innumerable disease conditions is dependent largely or entirely on X-ray examinations and the treatment of several types of disease likewise requires Roentgen irradiation. The debt of mankind to Roentgen and his fellow workers in the field of physics and engineering cannot be repaid easily.

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50 Years of X-Ray Progress in Europe

The penetrating power of the X ray was discovered in Europe in 1895 and since then European scientists have made many contributions to X-ray development. This is a presentation of some of the important aspects of their research as conducted in one company.

A HALF-CENTURY ago the penetrating power of X rays, or Roentgen rays as they are known in most European countries, was discovered by William Conrad Roentgen, a 50-year old professor of physics at Wurzburg, Germany. For this discovery Roentgen, who was born in Lennep, Germany, in 1845, was awarded the Nobel Prize in 1901.

Roentgen's momentous discovery was made while experimenting with a Crookes tube, a highly evacuated glass container into which two electrodes, an anode and a cathode, were fused. At that time physicists were interested in cathode rays which had been discovered in 1876 but Roentgen was the first to obtain fluorescent action when he allowed the discharge from a powerful Ruhmkorff induction coil to pass through his tube and the rays emitted struck a screen covered with a barium platino-cyanide accidentally left lying in the vicinity. When the slightness of the absorption of X rays by all kinds of nontransparent substances, such as wood and cardboard, as well as the formation of sharp shadow images by metallic objects was determined, Roentgen realized that his rays could be employed for medical, diagnostical and technical purposes. Their value to medical therapy also was recognized quickly and as early as 1905 a special tube had been constructed for the so-called "cavity therapy." Unfortunately, in those days there was no question of protection against the X ray, whose action on the human organism still was unknown, nor of protection against high voltages, so that several scientific pioneers lost their lives as a result of excessive irradiation.

Only one of the most important properties of the X ray, its electromagnetic character, was not demonstrated by Roentgen himself and even that he attempted to prove. It was not until 1905 that Haga and Wind, with primitive means, succeeded in demonstrating diffraction phenomena with X rays. In 1912 Laue, Friedrich, and Knipping published their diffraction spectra, obtained by the scat-

Based on "50 Years of Roentgen Rays" by J. H. van der Tuuk, in charge of X-ray tubes and rectifiers, X-ray Department, N. V. Philips Gloeilampenfabrieken, Eindhoven, Holland.

tering of X rays by natural crystals, a discovery which formed the basis of modern crystal-structure analysis by means of X rays and which also opened the way to X-ray spectroscopy.

DEVELOPMENT OF THE X-RAY TUBE

Following the first X-ray tube, the so-called gas tube was introduced (see Figure 2). This glass tube was filled with a gas (for example, air) at a pressure of about 0.01 to 0.001 millimeter of mercury. Under the influence of high voltage, 30,000 to 50,000 volts, the positive ions always present in the gas moved towards the negative electrode (cathode) and upon collision with it they freed negative electrons or cathode rays. These negative electrons, because of their small mass, moved in the field at a great speed toward the positive electrode (anode) and upon striking it or the glass wall excited electromagnetic vibrations, the X rays. Roentgen quickly discovered that the penetrating power of the ray increased rapidly with an increase of the voltage of the tube, and that an increase in intensity was evident with an increase in current.

Roentgen also discovered that the efficiency of the tube was enhanced by introducing opposite the cathode a third electrode, the so-called anticathode, which is usually in direct electrical connection with the anode. By means of this improvement practically all of the electrons were captured by the metal of the anticathode, instead of part of them striking the glass wall. It was not long before platinum was in general use as material for the anticathode since, under otherwise similar conditions, the efficiency of the process of excitation of X rays was found to be approximately proportional to the atomic weight of the anticathode substance.

EARLY IMPROVEMENTS

During the first 15 or 20 years of X-ray history many important technical improvements were introduced. The surface of the cathode (an aluminum cathode proved most efficient) was made concave for the more perfect focusing of the cathode-ray beam on the anode. The anticathode was water-cooled in order to obtain a higher continuous loading of the tube. Finally, an automatic regulation of the gas pressure corresponding to a certain length of spark was instituted in order to insure the regular functioning of the tube. In this way, a development period of almost two decades saw a capricious laboratory instrument evolve into a commercial product with which the experienced X-ray technologist could carry out very useful work.

Meanwhile, in the United States, W. D. Coolidge directed research that perfected a ductile drawn-tungsten wire which made possible a tungsten filament as well as a tungsten anticathode in X-ray tubes. Investigations by Edison and Richardson had discovered the "thermionic emission" of incandescent metals and, in 1913,

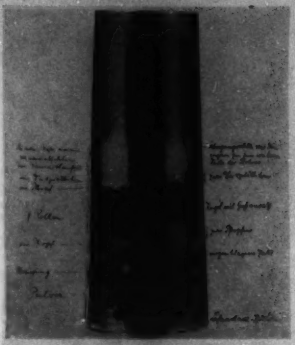

Figure 1. Historical X-ray photograph of an old sporting gun taken by Professor Roentgen

German handwriting is Roentgen's and refers to certain details of the picture

Coolidge constructed a "powerful Roentgen-ray tube with a pure electron discharge." This was an essential step in the process of rendering the X-ray tube an electrotechnically reproducible instrument. The improved vacuum technique (Langmuir) had made it possible to evacuate the glass tubes with metal electrodes thoroughly so that the electric current, which in tubes with tungsten filaments passed from the cathode to the anticathode, consisted of a completely controllable current of electrons. With this innovation the current through the tube as well as the voltage could be chosen practically independent of each other, an impossibility with the gas tubes. Regeneration arrangements were no longer necessary, the tube was evacuated to the extreme attainable vacuum, and the mysterious third electrode was no longer necessary. The same piece of metal served as target and as conductor for removing the electrons. It was also very important that these electron tubes, in contrast to the old gas tubes, were self-rectifying in principle, so that good-quality transformers could be used to feed them instead of the old-fashioned induction coil with complicated interrupters. High-vacuum rectifiers then appeared as a further step toward reliable X-ray apparatus.

As previously mentioned, Coolidge introduced the tungsten anticathode which offered several advantages over the platinum used almost exclusively until then. While the atomic number differed only a little, the melting point of tungsten (3,400 degrees centigrade) is considerably higher than that of platinum (1,770 degrees centigrade), its heat conductivity is about twice as good, and, at higher temperatures, tungsten has a much lower vapor pressure than platinum; properties which make tungsten the ideal material for anticathodes. Both types of anticathode used by Coolidge, the wrought-tungsten stem for therapy tubes and the copper-backed tungsten plate for diagnostic tubes, still are used in modern X-ray tubes.

IMPETUS OF WORLD WAR I IN NETHERLANDS

In the Netherlands World War I was indirectly responsible for a new activity in the X-ray field. The country, as a neutral in that war, practically was cut off from the United States, England, and Germany, and Dutch roentgenologists were forced to go to native industry for their equipment. In Eindhoven, for example, the Philips Company was obliged to establish a special department for the repair of defective tubes which, in turn, led to the later creation of a separate research and development group.

By 1923 a method of welding chrome-iron to glass had been discovered and this was applied in the manufacture of X-ray tubes (the "Metalix" tube of the Philips Company). The main characteristic of these tubes was that the essential part, the discharge chamber proper, consisted of metal instead of glass. This made it possible to decrease the diameter of the tube considerably as the chance of breakdown of the remaining glass wall was reduced to a minimum. Moreover, the opening in the metal for the window could be chosen so that only a cone of useful X rays left the tube. By means of a lead covering and with the help of a tungsten plate in the cathode, direct primary rays were prevented from escaping from the tube except through the glass window, which removed the danger from X rays

Figure 2. Early-type gas-filled X-ray tube

It is provided with a radiator cooling system and a regeneration device

Figure 3. Shielded tube for cavity-therapy apparatus

Total length is 50 centimeters, total weight is approximately 5½ pounds

Figure 4. Historical types of X-ray tubes

when the tube was used with judgment and by experts. In another tube developed by that company the anode was synonomous with the rotor of an electric motor and was made to rotate by a rotating field shortly before and during the time the tube was loaded. In this way a sharper image of the rapidly moving organs of the human body (the heart, lungs, and stomach) could be obtained. Another development was the construction of a portable diagnostic X-ray apparatus with complete protection from high voltage and X rays in 1928.

A whole series of X-ray diagnostic apparatus for various general and special uses was developed within a short time and appeared on the market. This apparatus embodied the principle of complete automatic control which meant that upon the choice of voltage and exposure time the tube was charged automatically with approximately the maximum permissible load.

TUBES FOR THERAPY

Therapy tubes must operate at much higher voltages than diagnostic tubes and, as a result, the secondary electrons reflected from the focus have an important influence on the electrical behavior of the tube. With the introduction of a metal partition plate by which the discharge space between anode and cathode is divided into two parts so that only the primary electrons from the filament can pass through a narrow opening in the grounded partition plate, it was found possible to manufacture sealed rayproof tubes having a lifetime of several thousand hours for 200-kv, or even 400-kv, pulsating or constant direct current. (At the Cancer Hospital, Louvain, Belgium, four 400-kv tubes have been in daily use since 1935.) The use of a barium getter, which absorbs the last traces of active gases in the tube, has played an important part in these tubes as it has in the construction of a sealed 800,000-volt cascade tube. The cascade tube consists of three sections in series connected by metal tubes. In the first section there is a tungsten filament, in the third an anode. The electrons emitted by the filament are accelerated in the first section, pass through the first connecting tube, and again are accelerated in the second section. They then pass through the second connecting tube and undergo a third acceleration in the last section before they finally strike the anode. Each of the three sections carries one third of the voltage. Such a tube has been in use at the Cancer Institute, Amsterdam, since 1937.

ARTIFICIAL RADIOACTIVITY

Another interesting field in connection with the X ray is that of artificial radioactivity. Since Curie and Joliot first succeeded, in 1934, in making radioactive substances by artificial means, physicists all over the world have been exploring this new field of nuclear physics with great enthusiasm. The most suitable projectile for penetrating the atomic nuclei, and thus initiating various nuclear reactions, was found to be the neutron. The neutron is a particle of the weight of a hydrogen atom, but with no electrical charge, and is capable of easily entering the positively charged nucleus. The production of neutrons, which is carried out most effectively by the bombardment of lithium by heavy hydrogen ions, requires discharge tubes and generators for very high voltages as the efficiency of the reaction increases rapidly with the velocity of the ions of heavy hydrogen. In this connection special high-voltage apparatus of the cascade type, up to 2,000,000 volts, was built consisting of one transformer and several tubes and capacitors, each for 200 kv (see Figure 6) and neutron tubes were produced.

Apart from medical X-ray apparatus, special X-ray outfits for industrial purposes and crystal analysis have been made available. Although the efficiency of the microscopic testing of materials with the help of X rays had long been known, it was not until about 1935 that this X-ray testing, stimulated by several cases of official requirement of this testing for the quality of electrically welded seams, was applied on such a large scale for this purpose. A tube was perfected which has a specially constructed grounded anode, can be cooled with water from the mains, and may be loaded continuously with 2,000 watts on a focus of four millimeters to a maximum of 150 kv peak. With this instrument it is possible to photograph the most commonly occurring welded joints up to a thickness of four centimeters of steel, while fluoroscopy can handle a thickness of two centimeters. For the fluoroscopic X-ray testing of heavy light-metal castings special tubes with a thin glass window are preferable.

During World War II X-ray equipment was developed, consisting of a transformer and a tube with rotating anticathode, which was provided with a focus of the order of 0.5 to 0.7 millimeter. A tube with this extremely small focus is continuously loadable up to 100 kv peak alternating current and 600 watts continuous current. The point focus makes it possible to bring the object to be tested to within a few centimeters from the focus and to examine the object in its natural size (screen directly behind the object) or to examine an enlarged image (distance between screen and object twice or three times as long as the distance from focus to middle of the object). As the focus is practically a point, the enlarged image on the screen does not lose its definition immediately. On the contrary, upon enlargement the details become visible much more quickly and much more easily, because the shadow image and its detailed structure become relatively larger and sharper compared with the lack of sharpness of the grain of the fluoroscopic screen. With a normal focus

of a tube with a stationary anode of two millimeters, this enlarging technique cannot be applied because in that case the geometrical lack of sharpness of the shadow image caused by the dimensions of the focus spoils the fluoroscopic image. It is even impossible to place an object at approximately the same distance from the focus as the thickness of the object because of the geometrical lack of sharpness.

CRYSTAL-STRUCTURE ANALYSIS

In 1930 transportable, entirely protected X-ray equipment was made available for crystal-structure analysis. This apparatus functions at about 45-kv alternating current and about five milliamperes. Tubes with anticathodes of copper, cobalt, iron, molybdenum, or tungsten and a focus of 1.5 millimeters, depending on the sample to be investigated, can be interchanged easily. Fan-cooled anodes are used. Later the unipolar grounded tube for microstructure was developed in which a water-cooled anode is used so that a loading of 50 to 60 kv peak at 20 milliamperes continuous current can be given on a line focus of 1.2 square millimeters. In addition to tubes with copper, tungsten, and molybdenum anodes, tubes with cobalt, iron, and chromium anodes also are produced. The tubes are provided with four or two windows of low-absorbent Lindemann glass. For these tubes a transportable high-voltage and radiationproof unit has been developed and various special cameras can be furnished as well. Particulary in the manufacture of artificial silk and quartz crystals for transmitters, industrial microstructure examination is employed on a large scale and the testing of the product with X rays forms a necessary link in the manufacturing process.

Figure 6. Neutron generator for 1,250,000 volts (Eindhoven, Holland)

In the foreground is the 13-foot acceleration tube with three insulating pillars for the shielding cap. Below is laboratory in which transmutations take place. To rear is high-voltage generator whose successive stages are connected by resistance (approximately 13 feet long) to corresponding sections of acceleration tube

While industrial X-ray technology was progressing there also was progress to report in the medical field. For stomach examinations "serial casette changers" were developed by means of which the film can be slid behind the screen with a single motion of the hand and the apparatus and tube were arranged for automatic and rapid changing over from fluoroscopy to photography. The increasing employment of X-ray examination for tuberculosis led not only to series fluoroscopy but also to mass chest radiography by taking miniature pictures of the image on the fluorescent screen. For the operating room an apparatus was developed which facilitates the removal of bullets and shell splinters. By means of X rays two beams of light are so adjusted that their point of intersection falls exactly on the bullet. The surgeon thus sees two light spots on the skin, can make his incision there, and can be guided further to the bullet by these beams of light. In addition, the "heart-phase switch" which enables the doctor to take an X-ray photograph at a certain phase of the heartbeat and an "exposure automat" which automatically switches off the tube when a certain density is reached have been realized experimentally.

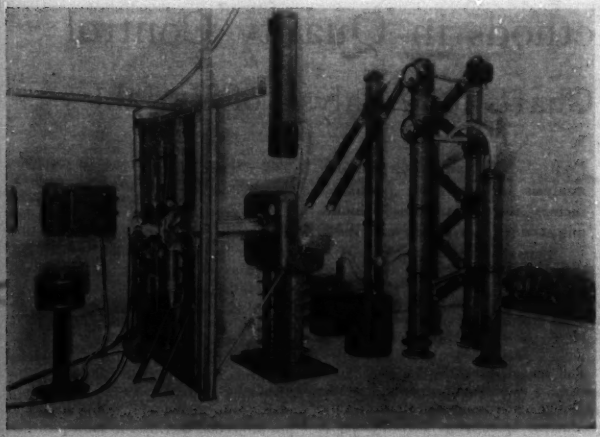

Figure 5. Complete neutron generator for 300 kv (Paris, France)

In the high-voltage room (right side of screen) are the canal-ray tube and the high-voltage generator. At extreme right is a 50–500-cycle converter used for feeding the positive-ion source. The isolated cooling pump is above the tube, one end of which protrudes through the screen into the workroom. Here neutrons are produced on a target which is connected to ground

X-RAY PROGRESS DURING WORLD WAR II

When the Germans invaded the Netherlands in 1940 the manufacture of new types of X-ray equipment in Eindhoven was brought to an end. The object was to manufacture as little as possible which might be of help to the German war ef-

fort. However, development proceeded. During the occupation plans were prepared for the manufacture of special hard glasses for discharge tubes at high voltage and for suitable alloys for hard glass–metal seals. Since 1940 X-ray and high-vacuum tubes of hard glass have been produced. In 1941 a small diagnostic tube with a stationary anode was put on the market which weighed only about 20 pounds. The hard-glass tube is placed inside a grounded rayproof and shockproof metal shield filled with oil. It is normally suitable for a power of more than 70 watts continuous at alternating and direct voltages up to 100 kv peak but, if desired, the continuous power can be increased by extra cooling of the jacket. A similar tube is suitable for a continuous power of 150 watts without any additional cooling of the shield to working voltages of 100 kv peak. These tubes are the double-focus type.

RECTIFIERS

Typical rectifier tubes for X-ray purposes are the high-vacuum and gas-filled types. The high-vacuum tubes have a metal discharge chamber, the metal wall of which is at the same time the anode, surrounding the cathode filament. By this means the saturation emission at a given temperature of the filament is reached at a much lower and more reproducible anode voltage than in glass tubes. In the latter the cathode is not surrounded by the anode and the glass envelope usually takes on a negative charge and so functions as a grid. The gas-filled tubes contain mercury vapor and the discharge phenomenon in the transmitting phase is quite different from that in a vacuum tube. The strong negative space charge is lacking; on the contrary an arc is formed between the filament and the anode. With a momentary emission of 1,500 to 2,000 milliamperes the voltage difference between anode and cathode amounts to only about 25 to 30 volts. The advantages of these tubes are practically no voltage drop and a very low filament wattage. However, at very low room temperatures they are difficult to start and at high temperatures there is a chance of breakdown in the blocking phase.

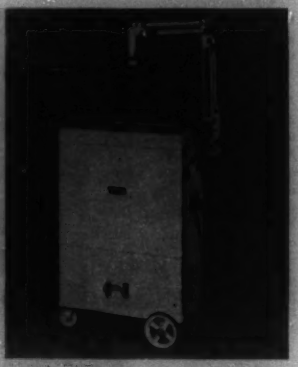

Figure 7. "Metalix" therapy apparatus suitable for short-distance and body-cavity irradiation

Mounted on wheels, the unit also incorporates a stand for the tube

A third tube combines the advantages of the high-vacuum and gas-filled tubes but does not have the disadvantages of the latter. This type is a high-vacuum rectifier with a thoriated-tungsten filament. A diagnostic tube of this type at an emission of 2,000 milliamperes has a voltage drop of about 2,000 volts and a filament power of about 35 watts. These tubes have a long life and require a high vacuum.

This is just a brief résumé of some of the developments in the Netherlands that have helped to make the X ray indispensable to modern life. Its importance in both the pure and applied sciences has long been recognized in Europe, where the penetrating power of the ray was discovered, as well as in the United States. European scientists have contributed a great deal to X-ray technology and, with the resumption of peace, undoubtedly will continue to contribute much more in the future.

Statistical Methods in Quality Control

VII. Control Charts for Analysis of Variables

Control charts and their use of analysis to determine possible factors in the process which might need correction are discussed in this article.

ENGINEERS recognize that control and interpretation of variations in processes and operations constitute a major problem. This is true whether the aim is to meet specifications consistently, to reduce variations for design improvement, or to interpret the reliability of experimental results. Obviously variations in results come from variations in the factors underlying the creative process. Each factor in turn is governed by a host of others. In short, the character of a result arises from a large number of causal factors. When a system contains a large mass of relatively small causal factors, indistinguishable in their individual influences, the resulting variations are said to be due to chance. When a predominant and therefore identifiable factor changes, we speak of an assignable cause or an assignable variation.

The statistical quality-control chart is sometimes considered primarily a tool for attaining better control during repetitive production operations. Nevertheless, its scope of application includes analysis of data. This article illustrates the latter.

As previously discussed in this series, an essential of control-chart procedure is proper classification of observations—rational subgrouping*—on a basis of possibly associated factors, such as machine, operator, supplier, and so forth, or upon time, that is, production sequence. The chart therefore can be used to test homogeneity, that is, for assignable peculiarities associated with a particular classification, as well as for removable instabilities and capabilities of processes in time. In fact, such analysis precedes the setting of operating control standards for corrective action during continuous production.

In illustration, visualize a multiple-head machine, essentially a battery of individually operated processes, molding a plastic base around a projecting pin. The pin projection is critical in subsequent assembly, and has specification limits of 0.036 inch and 0.065 inch. Process variables or factors influencing control of pin

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One of a series of articles prepared in the AIEE subcommittee on educational activities and sponsored by the AIEE subcommittee on statistical methods.

Personnel of the AIEE subcommittee on educational activities: J. Manuele, H. F. Dodge, A. I. Peterson, and R. E. Wareham.

* Rational subgrouping has been discussed previously in this series, and in reference 1, page 48, and reference 2, page 9.

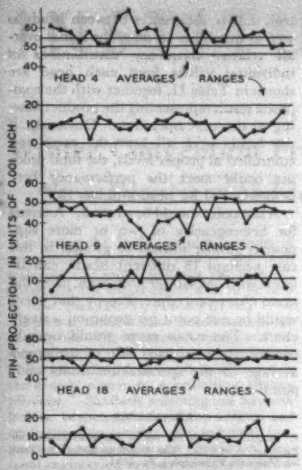

Figure 1. Control charts for heads number 4, number 9, and number 18

projection include supplied over-all pin lengths and plastic-material quality, where variability tends to influence all heads or machine units simultaneously, and individual head adjustments and characteristics substantially independent of each other.

In planning the rational subgrouping of test samples for initial analysis, it is desirable to reflect possible influences from principal over-all factors, as well as from those peculiar to individual heads. For reasons beyond this discussion, the sample size for any one head and time was set at seven in this case, although four or five usually suffice. Such samples per hour from each head provided the necessary data.

The average and range were calculated for each sample of seven. Table I illustrates the results for the first 25 hours for three of the heads, in units of 0.001 inch. The next step was the setting-up of control limits for analyzing the results. In each case, the mean value of ranges within samples provided an approximation of the chance variability or dispersion, without inflation from the instabilities in time and from the assignable differences between heads. To assist in comparing head performances, the central line in each case was taken as the midpoint of specification limits, that is, 0.0505 inch. Using the procedure outlined in reference 2, the control-limit calculations* for head number 18 are illustrated by

For averages:

$$\bar{X}' \pm A_3\bar{R} = 0.0505 \pm (0.419)\ (0.0112)$$
$$= 0.0505 \pm 0.0047$$
$$= 0.0458 \text{ and } 0.0551$$

* For technique and factors for calculation see reference 1, pages 49–50.

For ranges:

Central line $= \bar{R} = 0.01124$

Limits $= D_3\bar{R}$ and $D_4\bar{R}$
$= 0.076\ (0.0112)$ and $1.924\ (0.0112)$
$= 0.0009$ and 0.0215

The corresponding limits for the other two heads are

	Number 4	Number 9
For averages	0.0461 and 0.0549	0.0457 and 0.0553
For ranges	0.0008 and 0.0200	0.0009 and 0.0222

In this case, comparing heads which are supposed to be similar in performance and which in the data appear substantially homogeneous, it is permissible to average all sample ranges from all heads, which for the three units illustrated gives us

$\bar{R} = 0.01107$

Limits for averages $= 0.0505 \pm 0.419\ (0.01107)$
$= 0.0505 \pm 0.0046$
$= 0.0459$ and 0.0551

Limits for ranges $= 0.076\ (0.01107)$ and $1.924\ (0.01107)$
$= 0.0008$ and 0.0213

In examining the control charts, many interesting inferences were suggested. First, it was apparent that head number 4 operated at too high a level, as well as being out of control. Also, head number 9 performed at too low a level, as well as being out of control. Head number 18 operated in control and at the proper level. The machine setter's earlier claim that the

Table I. Control Sample Averages and Ranges

(Sample Size is Seven)

Date	Hour	Head Number 4 $\bar{X}$	Head Number 4 R	Head Number 9 $\bar{X}$	Head Number 9 R	Head Number 18 $\bar{X}$	Head Number 18 R
-3	1	61	9	54	5	50	8
	2	59	11	49	12	51	3
	3	58	13	47	18	49	12
	4	53	15	50	23	45	15
	5	58	3	44	6	53	6
	6	52	14	44	8	50	11
	7	52	12	44	8	49	11
	8	66	8	48	8	55	7
9-4	1	69	8	41	15	55	6
	2	58	12	37	10	47	12
	3	60	8	32	24	49	13
	4	59	13	41	19	49	19
	5	45	12	41	6	52	9
	6	65	16	44	14	50	20
	7	59	15	35	10	52	6
	8	47	11	50	11	54	10
9-5	1	58	12	42	6	51	9
	2	53	4	53	6	55	12
	3	53	8	53	11	51	9
	4	65	10	52	9	49	8
	5	55	4	40	13	51	16
	6	57	7	47	13	50	19
	7	58	7	49	9	53	4
	8	50	11	47	18	52	10
	9	51	17	45	7	51	14
Sum		1,421	260	1,129	289	1,273	281
Number of Items		25	25	25	25	25	25
Average		56.84	10.40	45.16	11.56	50.92	11.24

Table II. Head Relative Frequency Distributions

(Units of 0.001 Inch)

Cell Limits	Number 4 (Per Cent)	Number 9 (Per Cent)	Number 18 (Per Cent)	Composite (Per Cent)	
20.5–23.5		0.6		0.2	
23.5–26.5		0.0		0.0	
26.5–29.5		1.1		0.4	2.7
29.5–32.5		1.7		0.6	
32.5–35.5		4.6		1.5	
35.5–38.5		4.6	1.1	1.9	
38.5–41.5	1.7	18.3	2.9	7.6	
41.5–44.5	1.1	13.7	6.3	7.1	
44.5–47.5	6.9	18.8	13.7	13.1	
47.5–50.5	9.1	12.6	21.8	14.6	
50.5–53.5	10.3	11.4	24.0	15.3	93.6
53.5–56.5	18.9	9.1	17.7	15.3	
56.5–59.5	20.6	2.3	9.1	10.8	
59.5–62.5	11.4	0.6	3.4	4.9	
62.5–65.5	9.1	0.6		3.0	
65.5–68.5	5.1			1.7	
68.5–71.5	2.9			1.0	3.7
71.5–74.5	2.9			1.0	
	100.0	100.0	100.0	100.0	

trouble originated with the poor control of pin lengths supplied—an over-all effect—obviously was refuted, as the same material was used in head number 18 as in the others. Adjustment of the head levels was a relatively simple job as soon as the faulty units were identified, although there still remained some lack of control or stability about the average levels. Here again, it was difficult to defend the claim that over-all influences such as incoming material were to blame, since trends and short-run violations of limits did not correlate among the heads; in fact did not appear in head number 18 at all. Investigation guided by this information subsequently proved that fouling and play in positioning devices were the causes; that is, insufficient maintenance.

A second aspect of analysis, particularly with reference to the setting up of control standards for subsequent corrective supervision, was the approximation of attainable control, in the sense of dispersion with respect to specification limits and scrap. Since the mean ranges tended to indicate the degrees of simple chance variability alone, attainable for the product over-all if the assignable causes of instability were kept out of the process, it was possible to check both the rationality of the specification limits and the justice of control limits to be established. Using the known relationship of a mean range, which is substantially stable in these charts, and the controlled long-run dispersion of single observations, we calculated the limits on each side of specification bogey, or midpoint, that could include practically all of the results under controlled conditions.* For head number 18:

$$\bar{X}' = 3\frac{\bar{R}}{d_2} = 0.0505 \pm 3\,(1.0112/2.704)$$
$$= 0.0505 \pm 0.0124$$
$$= 0.0381 \text{ and } 0.0629$$

Corresponding calculations for the other heads provide

Number 4: 0.0390 and 0.0620
Number 9: 0.0380 and 0.0630

Such calculations for all head ranges together provide limits of 0.0382 and 0.0628.

Since there was practical compatability of these possible specification limits with the established ones of 0.036 and 0.065, the typical claim of "robbing the shop" did not stand up.

To demonstrate the effect of lack of control, that is, differences between heads as well as instability in time, the initial over-all relative frequency distributions of individual values from each head are shown in Table II, together with the composite result representing the product flowing to the next operation. Obviously, if the heads were all kept the same and controlled at proper levels, the total product could meet the performance here demonstrated by head number 18.

A last point should be stressed. Analysis for heterogeneity of two or more supposedly similar sources or groups, in this case perhaps 15 different heads, can be made with one sample from each, using the same chart procedure, except that there would be one point per group on a single chart. The mean range would provide control limits on each side of the grand average or the specification limits midpoint.

* See discussion of inclusive limits in the second article of this series in the July 1945 issue of *Electrical Engineering*.

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Betatron Developed for Production of 100,000,000-Volt X Rays

With the removal of wartime restrictions, details concerning the construction of a 100,000,000-volt betatron or electron accelerator have been released by the research laboratory of the General Electric Company, Schenectady, N. Y. The new machine emits a 100,000,000-volt electron stream that produces X rays of the same energy and, it is said, can generate radiations in the laboratory which formerly were available only in the cosmic rays.

Located in a special building with concrete walls three feet thick as a protection against the dangerous rays emitted, the principal part of the betatron is a 130-ton electromagnet of laminated silicon steel and its heart is a toroid or doughnut-shaped vacuum tube of glass, 74 inches in diameter, which lies in the center between the two poles of the magnet.

The betatron operates on ordinary 60-cycle alternating current and when the machine is operated at full power, a beam of X rays two degrees in diameter is emitted. The betatron also may be operated at lower power but the resulting production is not very strong.

The 100,000,000-volt electron accelerator evolved from a 2,300,000-volt table-size model constructed in 1939 and a 20,000,000-volt betatron completed in 1941.

Figure 1. View of 100,000,000-volt induction electron accelerator

In the foreground are E. E. Charlton (left) and W. F. Westendorp (M '43) who were responsible for the design and construction of the machine

INSTITUTE ACTIVITIES

Winter Convention Program Will Explore New Frontiers of Electrical Engineering

Initiating the Institute's postwar series of conventions, a program replete with both technical and social activities has been arranged for the winter convention to be held in New York, N. Y., January 21–25, 1946. All prewar features have been restored, including the dinner-dance, smoker, and inspection trips. The challenging possibilities of the immediate future will be discussed at the general session by a prominent electrophysicist. Similarly reflecting this forward-looking keynote, many of the sessions and conferences comprising the technical program will explore the new frontiers of electrical engineering in their respective specialties. Convention headquarters will be in the Engineering Societies' Building, 33 West 39th Street. Early registration is urged.

Registration will be enforced and nonmember fees of $2 will be required. Only persons registered may attend sessions.

GENERAL SESSION

The Institute is fortunate in having J. R. Dunning, a prominent electrophysicist of broad vision and extensive research experience in the field of nuclear physics, to address the meeting. Active in the investigation of atomic fission for many years prior to his recent connection with the atomic-bomb project, Doctor Dunning is in an exceptional position to place before the electrical engineering profession the great possibilities of the future. His address will be inspirational, serving as a keynote for the forward outlook of the entire technical program, from which may come new and improved ideas in specialized fields of activity.

Two of the highest engineering honors, the Edison Medal and the Hoover Medal, will be presented at this session. Details of the awards will be announced later.

CONFERENCE ON INSTITUTE ACTIVITIES

The Institute is confronted by problems of growing urgency both in its relations to the engineering profession at large and in its relationship to highly specialized organizations and interests within its own general field. Early in this administrative year, the board of directors referred these problems to the committee on planning and co-ordination, who have appointed two special subcommittees to explore the professional and technical activities of the Institute in relation to those of other engineering and scientific societies and more particularly in relation to the desires and aspirations of the members of the Institute.

The relationship to other organizations is the easier part of the study. The desires and aspirations of the rank and file of the membership are more difficult of determination. This conference is intended as one of the first steps in sampling membership opinion on what the Institute should be doing as compared with what it is doing.

Members active in Institute affairs should take this opportunity to assist the subcommittees by giving thought to the problems in advance of the conference, by attending the meeting and stating their considered opinions and specific suggestions. It is hoped that every District and every Section will be represented by at least one member but the meeting is open to all members and their views on these possible new frontiers of the Institute will be welcomed.

TECHNICAL SESSIONS AND CONFERENCES

Technical sessions and conferences range through the whole realm of technical-committee activites. The sessions have been arranged to avoid conflict insofar as possible. Applied principles of electronics occur not only in the communications papers but also may be found in various papers throughout the program. Similarly, measurement technique may be found not only in the instruments and measurements sessions but also threads through many papers in other sessions. Abstracts of first available papers are given elsewhere in this issue.

CENTRAL STATIONS

In the field of power transmission one of the papers will analyze the lightning performance and construction of 220-kv lines for the past ten years. Another paper deals with formulas for conductor size according to the cost of resistance loss.

In the field of power generation one session will treat hydroelectric systems and another will be on excitation systems. The hydroelectric installations in this country and in Canada have played an important part in winning the war. In the past, however, very little has been published on the problems that are encountered in the design, operation, and maintenance of the hydroelectric installations, as compared with the steam plants. This series of papers is intended to give a representative cross section of the problems and experience relating to the hydroelectric systems.

The task of providing and controlling the excitation of large turbogenerators of the power system is being approached from a new angle. Instead of the conventional type of design, the motor-driven exciter, the electronic exciter, and the electronic voltage regulator are offered as a new solution of the problem.

In general, wartime requirements for protective devices did not bring forth any startlingly new developments. However, there have been some new and interesting applications of basically known devices which will be discussed in detail at the several protective-devices and relay sessions. These subjects will cover a range of protective relays, network protectors, new devices for the protection of series capacitors, pilot wire protection, and a number of interesting new circuit breakers. This program will be keyed in with the theme of "New Frontiers," as the discussions develop the new applications and the probable effect of new devices on future practice.

There will also be one conference session devoted to an informal discussion of transformer protection. In the past these conference sessions have been extremely helpful as a means of exchanging experiences.

As a means of helping to shape future practice, the users of protective devices are being encouraged to contribute papers recounting their experiences. It is expected that at least one such paper will be included in this program.

COMMUNICATION AND ELECTRONICS

In the field of communication three technical sessions and a conference on communication relays are in prospect. In addition there will be a joint session with the Institute of Radio Engineers, which will be addressed by a prominent speaker in the radio field. One of the sessions will be general with papers on transmission-line problems, telegraphy, infantry combat communications, and a turntable rejection filter. Another will be a symposium on sound recording. Radar will be the subject of the third session provided necessary clearances can be obtained. This session is sponsored jointly with the committee on electronics.

INDUSTRIAL POWER APPLICATIONS AND ELECTRIC MACHINERY

On the new frontiers of industry the committee on electronics has arranged a conference on "New Industrial Uses of Electronics Resulting From Wartime Developments." Each speaker will describe briefly some new application of electronics for peacetime use that has resulted directly or as a by-product from a wartime development. Some of the speakers will utilize demonstrations or sample devices in their presentations. Only about half the allotted time will be devoted to scheduled presentations. The remainder of the period will be available for questions or discussions of the ideas presented and, if time permits, for the suggestion or description of still other new applications of electronics by those in attendance.

Another session and conference will consider the voltage requirements and the possible use of higher voltages to provide more power for the industrial distribution systems of the future. An interim report will be presented, which may lay the groundwork for a final report. Other conference presentations will treat neutral grounding and the grounding of delta-connected transformers. One or two papers on induction heating also will be presented.

Machine tool and process drives will be the subject of another conference. New and more powerful drives for industry will be

Tentative Schedule of Events

Monday, January 21

9:30 a.m.—Protective devices
Communication
Conference on new industrial uses of electronics resulting from wartime developments

2:00 p.m.—Symposium on sound recording
Power system relays
Electric welding

Evening—Radiobroadcasts, theaters, etc.

Tuesday, January 22

9:30 a.m.—Protective devices
Conference on communication relays
Conference on industrial voltage requirements

2:00 p.m.—Radar
Conference on power relays
Industrial power applications

6:30 p.m.—Smoker at Hotel Commodore

Wednesday, January 23

10:00 a.m.—General session
Edison Medal presentation
Hoover Medal presentation
Address: Professor J. R. Dunning

2:00 p.m.—Conference on Institute activities
Conference on standardization of aircraft electric equipment
Conference on machine tool and process drives

8:00 p.m.—Joint meeting with Institute of Radio Engineers

Thursday, January 24

9:30 a.m.—Power transmission
Electric machinery
Instruments and measurements

2:00 p.m.—Electric machinery
Instruments and measurements
Conference on statistical methods applied to quality control

7:00 p.m.—Dinner-dance at Hotel Plaza

Friday, January 25

9:30 a.m.—Hydroelectric systems
Air transportation
Conference on lighting
Basic sciences

2:00 p.m.—Excitation systems
Air transportation
Conference on education

6:00–8:00 p.m.—Institute of Radio Engineers' party at Hotel Astor

discussed and there will be presentations on co-ordinated drives in the rubber industry and industrial application of Rototrol regulators.

In the field of electric welding, papers will be presented which deal with the characteristics of the electric arc, spot welding, and capacitor stabilization of arc-welding transformers as well as the design and measurements of capacitor-discharge transformers.

Two sessions on electric machinery have been scheduled at which problems of design, performance characteristics, and rating of electric motors will be treated.

AIR TRANSPORTATION

Engineers attacking electrical problems in aircraft are always on "New Frontiers." In one of the sessions the vital problem of rating electric apparatus will be presented as aviation's frontier, "service ceiling," advances higher and higher. Another paper will contribute a newly released study of aircraft-ignition problems. Still another will blaze new trails with an authoritative treatise on the new a-c system for very large airplanes and a companion paper will describe a precedent-setting circuit breaker for these airplanes. Other pioneering achievements to be presented include a system of electric gun charging and the application of carbon piles to aircraft motor speed-regulating devices.

In the conference on standardization of aircraft electric equipment the principal business will be the progress of subcommittees engaged in standardization activities. Anyone interested is invited to attend. Prepared memoranda from committee members and nonmembers will be welcomed and time will be made available for discussion from the floor by visitors.

HOTEL ACCOMMODATIONS

The hotel situation in the metropolitan area is acute and quite likely will remain so for some time. Members, therefore, are urged to make their plans early and arrange for accommodations directly with the hotel preferred. The Institute has no connections with any of the hotels and cannot undertake to make reservations.

NONMEMBER REGISTRATION REQUIRED

Arrangements are being made to enforce the rule that nonmembers attending the convention must register. Admission to all technical sessions will be strictly limited to those wearing the registration badges obtainable at the registration desk by nonmembers of the Institute on payment of the $2.00 nonmember registration fee. To avoid embarrassment and misunderstandings, members are urged to call this fact to the attention of their associates who are not members of the AIEE, but who may be planning to attend some of the sessions.

Popular Entertainment Features Restored for Convention

Smoker: The smoker, an event which fortunately we have been able to stage regularly throughout the war years, will be scheduled again this year on Tuesday evening, January 22, 1946, at the Hotel Commodore. Arrangements are being made so that you can get together with your friends for cocktails preceding dinner and show. Tickets for dinner and show this year are $6.50 each and tables can be reserved for six, eight, and ten by remittance in advance. It is absolutely necessary that you make your reservations now.

Dinner-Dance: Your convention committee had decided that the popular interest always evidenced in our dinner-dances of past years again warrants the revival of that affair as one of the features of the 1946 winter convention. The Plaza Hotel Grand Ballroom has been reserved for 7 p.m. on the evening of Thursday, January 24, 1946. Tickets for dinner and dance will be $8.00 per person. Tables can be reserved for eight and ten. For those who find it impossible to attend the dinner a very limited number of tickets for the dance only will be available at $3.00 per person. Please send in your reservation and remittance at earliest possible date so that the committee can make necessary arrangements.

Inspection Trips: An inspection-trips committee is engaged in setting up an interesting group of inspections. While definite commitments cannot be made at the present time as to places or installations to be visited, the committee hopes to be able to schedule a trip to the Bell Laboratories at Summit, N. J., an inspection of LaGuardia Airport, with an air trip over New York and vicinity; a complete inspection of an aircraft carrier, a large power station, and trips to other points of interest. Details will be available on the opening registration day at committee headquarters.

Special Trips for Women: A Women's Committee is now being organized to provide features of special interest to the ladies attending the convention. No details can be listed at this time, but an interesting program for the women is assured.

Theater and Broadcast Tickets: As a service to out-of-town members a limited number of theater tickets are being purchased in advance for Wednesday and Thursday evenings, January 23 and 24, 1946. Members from outside of the New York territory who wish to attend any of the shows listed below should send in the reservations with remittances at once. Please indicate first, second, and third choices, if possible.

Oklahoma	$4.80
Carousel	6.00
Bloomer Girl	5.40
Song of Norway	6.00
Follow the Girls	4.80
On the Town	4.80
Up in Central Park	6.00
I Remember Mama	4.20
Harvey	4.20
Life With Father	3.60

There will also be available tickets for a number of broadcast presentations. These tickets will be obtainable on application at the registration desk, but no definite listing of the broadcasts can be made at this time.

Future AIEE Meetings

Winter Convention
New York, N. Y., January 21–25, 1946

South West District Meeting
San Antonio, Tex., April 16–18, 1946

North Eastern District Meeting
Buffalo, N. Y., April 24–25, 1946

Southern District Meeting
May 13–16, 1946

Summer Convention
Detroit, Mich., June 24–28, 1946

Pacific Coast Convention
Seattle, Wash., August 26–30, 1946

Great Lakes District Meeting
Fort Wayne, Ind., late summer or early fall, 1946

AIEE Planning Committees Begin Their Searching Task

The two new subcommittees of the AIEE committee on planning and co-ordination are actively at work on their assignments to review the organization, methods of operation, and scope of the technical and the professional activities, respectively, of the Institute and of other engineering and scientific societies. This survey is intended to lead to specific recommendations of ways and means by which the Institute more effectively can pursue its stated objectives and thus better serve its membership. Activation of these new groups was announced in the November 1945 issue of *Electrical Engineering*, page 409.

Active assistance of the technical-program committee has been enlisted by the technical-activities subcommittee. Through individual technical committee chairmen information on the several national societies working in specialized fields related to those of the Institute's technical committees is being assembled. The technical-program committee also is continuing its efforts to achieve more efficient internal organization within and between the existing technical committees. As one chairman expressed it—"Let's put our present house in order, then see if we can plan a better one." M. D. Hooven (F '44), chairman of the technical-activities subcommittee, is also chairman of the technical-program committee and a member of the committee on planning and co-ordination. Other members of the subcommittee are F. A. Cowan (M '29), S. G. Hibben (M '45), H. M. Turner (F '44), and R. J. Wiseman (F '27), all of whom have been active over a period of many years in AIEE and industrial engineering fields.

The professional-activities subcommittee, under the chairmanship of T. G. LeClair (F '40) a member of the committee on planning and co-ordination, includes M. S. Coover (F '42), W. S. Hill (M '30), B. D. Hull (F '39), and F. E. Sanford (M '34), all of whom long have been active in Institute and professional affairs. This group is not as fortunate as their colleagues who are studying technical activities, in that they do not have a ready-made group of active members to call upon for support. Nor is their problem as clearly defined, in spite of the fact that much has been said and written about the proper place of the engineer in civic and professional affairs, his relation to collective bargaining, his economic status generally, and the bearing of his nontechnical interests on the matter of greater unity in the engineering profession. Thus they will need, and are desirous of receiving, all the help which members of the Institute can give them.

Both groups are holding regular meetings planning their work and conducting preliminary investigations principally of an introspective character. The stated intention of these groups is to examine critically and constructively what the Institute is doing—and what it is not doing—to the end that the Institute's future program and policy may serve most effectively the actual needs and desires of the membership and of the profession. The working groups believe that worthwhile improvements in policy or procedure can be effected only if based upon competent and thorough-going diagnosis of existing conditions. They are seeking information as to symptoms and will welcome it from any quarter. AIEE vice-presidents already have been called upon as consultants, thus establishing one set of direct channels to and from the Districts. Others will be called upon as the studies progress, but spontaneous comments and suggestions direct from individual members or Section groups are especially invited.

An open clinic or conference scheduled to be held during the forthcoming winter convention will provide opportunity for the subcommittees to report progress and to state certain problems as they see them, and for full and frank discussion by any who may wish to participate. Meanwhile, members are urged to send in their ideas, their criticisms, their suggestions as to what they think needs to be fixed, to be changed, to be done. Communications may be addressed to any of the members of either group, to any of the vice-presidents, or to headquarters.

AIEE Board of Directors Meeting Held in Cleveland

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held in Cleveland, Ohio, October 18, 1945. The policy was adopted of holding the May and October meetings outside New York, N. Y., within a certain area, consideration to be given when choosing the time and place, to holding the meeting in conjunction with a District or Section meeting.

Members of the board of directors were elected to serve on the AIEE nominating committee as follows: C. B. Carpenter, C. M. Laffoon, F. L. Lawton, J. R. North, and H. B. Wolf. J. F. Fairman and W. B. Morton were designated alternates.

H. H. Henline, secretary, AIEE, was reappointed AIEE representative on the board of directors of the Engineering Societies Personnel Service, Inc., for the year 1946.

Sidney Withington was appointed AIEE representative on the main accrediting committee of the Engineers' Council for Professional Development, succeeding E. L. Moreland.

After a review of AIEE conventions and District meetings previously authorized tentatively, and consideration of new requests for District meetings the following schedule was approved for the year 1946: *Conventions*—Winter, New York, N. Y., January 21–25; Summer, Detroit, Mich., June 24–28; Pacific Coast, Seattle, Wash., during week of August 26–30. *District meetings*—South West, San Antonio, Tex., April 16–18; North Eastern, Buffalo, N. Y., April 24–25; Southern, in North or South Carolina, May 13–16, and Great Lakes, Fort Wayne, Ind., late summer or early fall.

The board endorsed resolutions, drafted at a conference of representatives of engineering organizations and the American Association for the Advancement of Science held in Washington, D. C., urging provision in any extension of the Selective Service Law for assigning quotas of selected young men to scientific and technical schools for training in lieu of active service with the Army and Navy—the purpose being to set in motion a procedure for overcoming the alarming deficit in trained technical personnel, so necessary for national welfare and defense, which has resulted from the applications of the Selective Service regulations.

Upon recommendation of the Welding Research Council, the board approved the idea of inviting the other Founder Societies to join in the sponsorship of the work of the Welding Research Council, for which the AIEE and the American Welding Society have been the sponsors in the past.

The board approved a change in name of the joint conference committee (consisting of the presidents, immediate past presidents, secretaries of the Founder Societies and the American Institute of Chemical Engineers) to "Engineers Joint Council." A suggested apportionment of the expenses of the Engineers Joint Council among the constituent societies according to their income from dues also was approved. The board approved a recommendation of the Engineers Joint Council that the National Society of Professional Engineers be invited to join the Joint Committee on Economic Status of the Engineer as a full participating member.

A budget for the appropriation year beginning October 1, 1945, recommended by the finance committee, was adopted amounting to $482,000. The budget included an appropriation for the committee on planning and co-ordination to carry out a project assigned to it by the board of directors, namely, that of reviewing the technical activities of the Institute and the Institute's relations with other organizations, and recommending any changes in organization or methods that may seem desirable.

Other actions taken included the following: Minutes of the meeting of the board of directors held August 1, 1945, and of the executive committee held September 14, 1945, were approved. Recommendations adopted by the board of examiners at its meeting September 20, 1945, were reported and approved. Upon recommendation of that board, the following actions were taken: 13 applicants were transferred and one was elected to the grade of Fellow; 68 applicants were transferred and 47 were elected to the grade of Member; one Member was reinstated; 200 applicants were elected to the grade of Associate, and 289 Students were enrolled.

Those present were: *President*—William E. Wickenden, Cleveland, Ohio. *Past president*—N. E. Funk, Philadelphia, Pa. *Vice-presidents*—C. B. Carpenter, Portland, Oreg., M. S. Coover, Ames, Iowa, J. F. Fairman, New York, N. Y., E. S. Fields, Cincinnati, Ohio, R. T. Henry, Buffalo, N. Y., L. M. Robertson, Denver, Colo., H. B. Wolf, Charlotte, N. C. *Directors*—P. L. Alger, Schenectady, N. Y., J. M. Flanigen, Atlanta, Ga., C. W. Mier, Dallas, Tex., S. H. Mortensen, Milwaukee, Wis., W. B. Morton, Bethlehem, Pa., J. R. North, Jackson, Mich., D. A. Quarles, New York, N. Y., W. C. Smith, San Francisco, Calif., W. R. Smith, Newark, N. J. *Treasurer*—W. I. Slichter, New York, N. Y. *Secretary*—H. H. Henline, New York, N. Y.

Other matters were discussed but not acted upon at this meeting.

1945 December Supplement Contents Announced

Papers which appeared in the AIEE technical-paper program for 1945 and were not published in the monthly *Transactions* section of *Electrical Engineering* or in the June supplement will appear in the December 1945 "Supplement to Electrical Engineering—Transactions Section." The December supplement will contain five technical papers, discussions of those papers, and discussions of the papers already published in the July–December monthly sections. Issuance of the December supplement will complete publication of papers and discussions received in 1945.

Copies of the supplement will not be available until some time after the first of the year, at which time published copies will be mailed to those who entered advance orders. Others then may obtain copies at 50 cents each from the AIEE order department, 33 West 39th Street, New York 18, N. Y.

Papers appearing in the December 1945 supplement, abstracts of which have been published in *Electrical Engineering* in advance of the meetings, are:

Electric Machinery

45-93—A Generalized Circle Diagram for a Four-Terminal Network and Its Application to the Capacitor Single-Phase Motor; *J. G. Tarboux (F '43).* Abstracted in the April 1945 issue, pages 156–7.

Communication

45-145—Report of Conference on Radio-Frequency Cables; *AIEE committee on communication.* Abstracted in the September 1945 issue, page 331.

45-146—A Study of Wave Shapes for Radio-Noise-Meter Calibration; *C. W. Frick (A '19).* Abstracted in the September 1945 issue, page 331.

45-263—Fundamentals of the Amplidyne Generators; *J. L. Bower (M '45).* Abstracted in the September 1945 issue, page 331.

Power Transmission and Distribution

45-141—The Frequency of Occurrence and the Distribution of Lightning Flashes to Transmission Lines; *R. H. Golde (A '42).* Abstracted in the September 1945 issue, page 332.

Welding Forum in Detroit

A resistance welding forum, sponsored by the industrial power group of the AIEE Michigan Section in collaboration with the Industrial Electrical Engineering Society, an affiliate of the Engineering Society of Detroit, and the Saginaw Valley Division of the American Welding Society was held at the Engineering Society of Detroit on November 9, 1945. A feature of the meeting was a lobby display of welded parts by the Resistance Welder Manufacturers Association. More than 200 attended the afternoon and evening sessions at which J. D. Gordon of Progressive Welder Company presided.

At the afternoon session the papers presented were: "Application of Capacitors to Flash Welders," by J. F. Deffenbaugh (A '42), Federal Machine and Welder Company, Warren, Ohio; "Resistance Welders," by J. E. Ponkow, Federal Machine and Welder Company; "Design and Measurements of Condenser-Discharge Welding Transformers," by T. W. Dietz, Taylor Winfield Company, Warren, and G. M. Stein (M '38), Westinghouse Electric Corporation, Sharon, Pa., and "A New High-Speed Control for Gun Welders," by Frank Roby (M '41), Square D Company, Milwaukee, Wis.

The evening session was devoted to two papers. They were: "Standard Types of Electronic Welding Control," by E. H. Vedder (M '35), Westinghouse Electric Corporation, East Pittsburgh, Pa., and "Off-Standard Resistance Welding Control," by G. W. Garman (M '43), General Electric Company, Schenectady, N. Y.

ABSTRACTS

TECHNICAL PAPERS previewed in this section will be presented at the AIEE winter convention, New York, N. Y., January 21–25, 1946, and will be distributed in advance pamphlet form as soon as they become available. Copies may be obtained by mail from the AIEE order department, 33 West 39th Street, New York 18, N. Y., at prices indicated with the abstract; or at five cents less per copy if purchased at AIEE headquarters or at the convention registration desk.

Mail orders will be filled AS PAMPHLETS BECOME AVAILABLE

Air Transportation

46-13—Pressure-Arc-Interruption Circuit Breakers for 400-Cycle Aircraft Electric-Power System; *B. O. Austin (M '43).* *15 cents.* This paper describes a lightweight circuit breaker for use on 208Y–120-volt three-phase 400-cycle a-c system for large aircraft. The circuit breaker is operated electrically remotely controlled with latched-in contacts. The design is suitable for paralleling generators and busses, circuit interruption, and manual or automatic synchronization, and interlocks are provided for use in various control circuits. Operating solenoids are designed for low-current requirements and for wide ranges of voltages and ambient temperatures. The circuit breaker performs under extreme variations in environment and performs satisfactorily under all conditions of operation. The arc-interruption mechanism is of the self-pressurizing type, having two breaks per phase. Speed of closing the main contacts of the circuit breaker, and speed of opening are very rapid, and the mechanism is adaptable to the required speeds for proper circuit protection co-ordination.

46-14—Electrical Measurements on Aircraft-Engine Ignition Circuits; *W. E. Berkey (M '39).* *15 cents.* A method of

Those present at the Southern District executive committee meeting held at Charlotte, N. C., October 27, 1945, were: W. J. Miller (F '43) and C. F. Sittloh (A '39)—Alabama Section; C. P. Almon, Jr. (A '37), W. O. Leffell (M '44), S. E. Lyons (A '37), and R. M. Alspaugh (M '41)—East Tennessee Section; C. W. Evans (M '40), J. M. Flanigen (M '25), G. F. Price (M '44), and R. O. Loomis (A '39)—Georgia Section; S. H. Gates (A '39), L. W. Anderson (A '32), and Brinkley Barnett (A '20)—Louisville Section; W. E. Lindemann (A '43), E. L. Biship (A '42), and R. C. Fuller (A '38)—Muscle Shoals Section; W. S. Leake (A '34), S. L. Kennedy (A '40), and A. D. Hargroder (A '43)—New Orleans Section; Otto Meier, Jr. (A '35), J. O. Kimbrey (A '44), W. J. Seeley (M '28), G. F. Bason (A '42), E. R. Davis (A '41), and H. W. Oetinger (M '35)—North Carolina Section; F. T. Tingley (M '31), J. L. Weeks (M '40), J. F. Rader (M '40), and D. H. Davis (A '40)—South Carolina Section; J. A. Rawls (M '27), C. H. Smoke (M '42), and J. H. Miller, Jr. (A '22)—Virginia Section; H. B. Wolf (M '37) vice-president, and C. B. Galphin (M '39) secretary, Southern District (4)

measuring ignition voltages with a cathode-ray oscillograph is described. Magneto and spark-plug voltage oscillograms covering several consecutive firing pulses were taken on a complete aircraft magneto ignition system under several engine operating conditions. Oscillograms taken with spark plugs firing in air show differences when compared with engine tests. An improved electronic oscillograph has been developed which is well adapted for ignition measurements.

46-1—All-Electric Gun Charging; *W. C. Rahn. 15 cents.* Power-operated charging means have been found desirable on remote automatic weapon installations for military aircraft. Chargers are used primarily to restore operation of a gun which has malfunctioned, but also may be used to set the weapon at safety or to stop a runaway gun. With the provision of suitable controls a charger can be made to function entirely automatically. Chargers have been predominantly fluid operated, whereas automatic or semiautomatic controls require electric power. An all-electric charger is considered which avoids the use of fluids and their associated installation and maintenance problems. The mechanism is mounted off the gun and connected by means of a flexible steel cable. This avoids transmission of the shock in firing to the charger unit and provides a maximum flexibility of installation. The design described will handle one weapon of 50-caliber or 20-millimeter size with fully automatic operation at a total apparatus weight of nine pounds. Two similar weapons may be served semiautomatically at a total weight of 11½ pounds.

46-3—Design Principles for A-C Electric Power Systems in Large Military Aircraft; *C. K. Chappuis (A '41), L. M. Olmstead (M '39). 15 cents.* This paper discusses the development of aircraft electric systems from the early days of aircraft development to super-aircraft now in the design stage and defines the electric systems now in use and proposed. The primary discussion covers the basic design problems of 400-cycle three-phase electric systems for aircraft. Voltage control, load requirements, operational characteristics, types of power supply, equipment, protection, regulation, and d-c requirements are considered. A brief résumé of future trends for electric-power requirements in aircraft is included with figures as to power requirements of some aircraft now in design.

46-4—A Carbon-Pile Speed Governor; *C. T. Button (A '26). 15 cents.* The advantages of a centrifugally operated carbon pile for control of the speed of a d-c motor are discussed, and comparison is made with the problem of automatic voltage control of a generator. Though it is applicable for speed regulation of various types of d-c motors, the discussion centers around the use of such a device for controlling speed and hence output frequency of aircraft inverters, where an 8,000-rpm d-c motor drives a 400-cycle generator. The features of design of the governor are described in some detail, and the operating characteristics are covered in a general way.

46-15—Effect of Altitude on Ventilation and Rating of Aircraft Electric Machines; *C. G. Veinott (M '34). 15 cents.* Fundamental problems involved in the cooling and rating of aircraft electric machinery at medium and high altitudes are discussed in this paper, primarily to assist users in the application of such equipment and to assist builders in designing equipment to meet the requirements. In addition, flight tests are reported which confirm in part the blast-tube theory developed in a previous paper. For blast-cooled generators an equation has been developed to show the maximum permissible output in terms of entering-air temperature and density, ramming-head pressure, and winding temperature. For motors curves of total winding temperature at rated load have been plotted as a function of altitude; these curves were plotted for selected values of sea-level temperature rise. Specific conclusions are drawn as to:

1. Permissible generator output as a function of altitude and sea-level rise.
2. Limiting sea-level temperature rises for motors on the basis of constant or reduced life at altitude.

This paper presents a qualitative method of analysis rather than a definitive solution of the problems involved.

Communication

46-7—Electronic Regeneration of Teleprinter Signals; *H. F. Wilder (M '45). 15 cents.* The paper describes a teleprinter signal regenerator using an electric delay network to control the signal-scanning process, which with associated circuits for the start-and-stop functions provides a regenerator without mechanism. The composition of an illustrative teleprinter character and its susceptibility to interfering line currents are discussed. The development and the electrical characteristics of the delay network are described, and the regeneration of the signal character is explained.

46-10—The Solution of Transmission-Line Problems in the Case of Attenuating Transmission Line; *George Glinski (A '43). 15 cents.* The mathematical and graphical method of finding the receiving-end standing-wave ratio q_R from the measurement on the measuring section located far from the receiving end of attenuating line is presented. It is shown that the magnitude of receiving-end voltage-reflection coefficient K_R is a function of the total attenuation of the line between measuring section and receiving end and of the standing-wave ratio q_3 at the point where measuring section is inserted. Graphical method of finding the receiving-end impedance in the case of attenuating line is shown to be essentially the same as in the case of the lossless line, if a correction for the total attenuation is properly introduced.

Electric Machinery

46-5—Transients in A-C Motors and Generators; *George S. Smith (M '26). 15 cents.* This paper presents a method for obtaining a physical conception of the variations in currents, voltages, magnetic fields, and so forth, which occur in rotating a-c machinery during changes in operation. Its purpose is not to present an accurate method of determining such values but to offer a method for obtaining a clear conception of such variations, which should be of value to the operator of such machinery or to the engineer or student who must make use of the more accurate mathematical methods available. The method of arriving at the results is by properly combining the determinable components known to be present. In certain cases these components are identified in the mathematical results of previous workers. As examples of the use of this analysis, certain operations of induction motors, three-phase alternators, and single-phase alternators are analyzed. Oscillograms taken in the laboratory on similar machines are presented for comparison.

46-6—Temperature Rise of Water-Cooled Power Transformers; *J. R. Meador (M '40). 15 cents.* This paper contains an analysis of the oil temperature rise of water-cooled power transformers. It is shown that by factoring the effect of viscosity oil temperatures can be calculated more accurately for a variety of conditions. Equations and curves are given with supporting test data for determining the temperature rise for different loads, ingoing water temperatures, and rates of water flow. The variations in temperature rise with load, water rate, and water temperature are appreciably different from published data on the subject. A discussion of winding hot-spot temperature, factoring the effect of oil viscosity, is included, although no new test data are given.

Electric Welding

46-9—Measurement and Effect of Contact Resistance in Spot Welding; *R. A. Wyant. 15 cents.* Spot welding is the simplest of the electric resistance-welding processes which depend upon the Joule effect, $H = I^2RT$, for the generation of heat. The total resistance, R, consists of the body resistance of the metal between the electrodes plus the sum of the sheet-to-sheet and electrode-to-sheet contact resistances. Circuits are described for the measurement of these contact resistances before and during the formation of the weld. These measurements have been most useful in improving methods for the removal of oxide films from the surfaces of aluminum-alloy and magnesium-alloy sheet prior to spot welding. The welds are more uniform, and the electrodes tend to require less frequent cleaning, when the initial contact resistance is consistently low. Little is known about contact resistance and its effects in spot-welding other metals. The need for further research in this field is emphasized.

46-12—Investigation of Arc-Starting Characteristics of D-C Welders With Reference to Electrode Freezing; *J. M. Tyrner (A '41). 15 cents.* The starting of the arc in d-c welders was investigated. It was found that the starting performance is determined by the length of the time the operator may leave the electrode and work in contact. Generators should permit at least 40 milliseconds contact duration. Five generators of different designs were tested. Oscillograms of the current surge during the contact period were taken. It was found that the striking performance depends on the shape of the current surge.

Instruments and Measurements

46-2—The Measurement of Large Varying Currents; *A. C. Johnson (A '42). 15 cents.* In oscillographic studies where it is necessary to measure current in the range of from 5 to 100 kiloamperes, one often must resort to the use of shunts because:

(a). Addition of a current transformer may change materially the impedance of the circuit.

(b). Current transformers for large currents are unwieldy.

(c). The current may be pulsating direct current, which would saturate a current transformer and render it useless.

It is extremely important that the shunts used be carefully designed and so connected into the circuit that the measuring-circuit current is proportional to and inphase with the shunt current. The paper includes an analysis and a basis for the design of shunts for measuring these currents, so that there will be no voltage induced in the measuring circuit for any of the frequencies of harmonic components normally encountered in the measuring of current of these magnitudes. Consequently, the measuring-circuit current will be a function only of a shunt current and the ratio of the resistance of the shunt to that of the measuring circuit.

Power Transmission and Distribution

46-8—Formulas for Conductor Size According to Cost of Resistance Loss; *H. B. Dwight (F '26). 15 cents.* In designing electric conductors, especially for overhead lines, it is often advisable to choose the size of conductor according to the cost of resistance loss. When the cost of reducing the loss at peak load by increasing the cross section of the conductor becomes equal to the cost of producing additional power, the point at which this occurs is given by a fixed value of current density. Formulas for determining the most economical conductor size in the foregoing way are given in this paper. These are designed to make the determination more convenient and easy. Formulas are given for aluminum conductors and for conductors of varying cost per pound, such as insulated conductors. The formulas indicate the advisability of taking account of the cost of power in choosing a conductor size. The marked difference between the cases where the conductors are owned by the company which generates the power and the cases where energy is purchased by the kilowatt-hour is brought out. It is shown that this application of Kelvin's law, for that is what the method really amounts to, does not involve uncertainty in most cases, but is a simple definite engineering problem based on data that are usually known. To specify heavier conductors, at improved economy, by these formulas does not mean a larger investment by power companies which have plant extensions in prospect. The matter is a choice in engineering design, whether a certain fraction of the investment should be made in conductors or in generator-station capacity.

Protective Devices

46-11—A New Submersible Network Protector of Higher Rating; *G. G. Grissinger (M '38), F. D. Johnson (A '41). 15 cents.* Although network protectors having a continuous ampere rating of 3,000 amperes 60 cycles have been available for several years, they are of the open type for use in dry vaults and therefore not suitable for submersible service. This paper outlines the problems involved and the methods used in developing a 3,000-ampere submersible network protector. Since a submersible network protector is practically airtight, the watts loss in the protector must be kept to a minimum, and special features must be incorporated to dissipate the generated heat if temperatures are to be limited to satisfactory operating values. There being no known means available for making reasonably accurate measurements of watts loss at very low voltages, a special test circuit was devised. The principle of operation of this circuit is described. Once how much heat energy has to be dissipated is known and the temperature differential available, it becomes a matter of radiation, convection, and conduction. The methods adopted for making use of these factors in a practical way are discussed.

PERSONAL . . . . .

G. Ross Henninger (A '22, F '43) AIEE editor-on-leave who has been serving as a lieutenant colonel in the Army Air Forces, has been released from active duty and has returned to the staff of *Electrical Engineering*. A member of AIEE headquarters staff since 1930, and editor since 1933, he was appointed a lieutenant colonel in the Army Specialist Corps in 1942 to serve as a liaison officer on the headquarters staff of the Corps at Washington, D. C., assisting the Signal Corps and the Air Corps with their technical-personnel requirements. In the latter part of that year he was commissioned a lieutenant colonel in the Army of the United States and transferred to the Army Air Forces with immediate assignment to the then newly established Air Service Command Headquarters at Patterson Field, Dayton, Ohio. As chief of the reproduction branch he initially was responsible for the procurement and development of printing and other facilities required for the reproduction of technical data for the Army Air Forces, but in June 1943 he was reassigned as assistant chief of the Maintenance Data Section serving as executive officer in the administration of the section's nine branches. In October 1944 he became chief of the section and a member of the staff of the chief of the Maintenance Division of what had by that time become the Headquarters, Air Technical Service Command, through consolidation of the original Air Service and Matériel Commands. His expanded duties included direct responsibility for procurement, preparation, publication and dissemination of the technical information required for the operation, maintenance, and repair of all equipment used by the Army Air Forces. Prior to entering into active military service in 1942, Colonel Henninger had devoted a substantial amount of his time for several months to the United States Navy Department in Washington in the organization of an editorial and review section in the office of the Secretary of the Navy for the co-ordination of Navy publications. **W. R. MacDonald, Jr.** (A '33, M '44) AIEE assistant editor who has been serving recently as acting editor (*EE, Apr '45, p 160*) has been appointed associate editor.

G. R. Henninger

C. E. Ide (A '16, M '38) formerly president, East Tennessee Light and Power Company, Bristol, has been elected executive vice-president and general manager of the Toledo (Ohio) Edison Company. Mr. Ide was born in Brayton, Iowa, and was graduated from Iowa State College in 1914 with the degree of bachelor of science in electrical engineering. He started in with the Cities Service system working first with the Denver Gas and Electric Light Company, and later with the Toledo Railways and Light Company, in the New York, N. Y., office of Henry L. Doherty and Company and the Meridian (Miss.) Light and Railway Company. During World War I he was a member of the science and research division of the Signal Corps of the United States Army, returning to the Doherty company and remaining for the next eight years. In 1927 he became vice-president and general manager of the East Tennessee Light and Power Company, and in 1940 became president. **H. H. Kerr** (A '17, M '26) formerly general superintendent, engineering and operation, Toledo Edison Company, becomes vice-president in charge of operations. Mr. Kerr was born in Fort Worth, Tex., and was graduated from the University of Colorado in 1914 with the degree of bachelor of science in electrical engineering. After graduation he spent one year in the test course of the General Electric Company, Schenectady, N. Y. Then after 14 years service with the Public Service Company of Colorado he transferred to Toledo as superintendent of the electrical operating department of the Toledo Edison Company. He was named general superintendent of engineering operation, maintenance, and construction in 1943.

A. L. Pollard (M '40) formerly general superintendent of light and power, Puget Sound Power and Light Company, Seattle, Wash., has been appointed general superintendent of operations. This assignment together with his duties under the previous assignment will add the task of general supervision of the generating and transmission system. Mr. Pollard was first employed by Stone and Webster as student engineer with the Houghton County Electric Light and Power Company, Houghton, Mich. After service with

the United States Army in World War I he returned to Stone and Webster working in Pawtucket, R. I., Tampa, Fla., El Paso, Tex., and for two years previous to his arrival in Seattle was power engineer for Stone and Webster Engineering Corporation, Boston, Mass. Mr. Pollard went to the Puget Sound Power and Light Company in May 1930 as superintendent of steam generation. In June 1934 in addition to his previous duties he was made superintendent of light and power of the central division, and two years later became general superintendent of light and power for the entire company. He continued in this capacity until his recent appointment.

William Henry Harrison (A '20, M '30 F '31) has been elected to receive the Hoover Medal for 1945 (*EE Nov '45, p 421*). General Harrison recently was elected vice-president in charge of operation and engineering, American Telephone and Telegraph Company, New York, N. Y., a position he held prior to 1940 when he went on leave of absence to head the production division of the War Production Board. He left the latter organization in 1942 when commissioned a colonel in the United States Army. Very soon after entering active duty he was promoted to brigadier-general and was given various assignments incident to Army production requirements. General Harrison was born in Brooklyn, N. Y., and was graduated in electrical engineering from Pratt Institute. He entered the employ of the New York Telephone Company in 1909. His work included apparatus inspection, assembling, and wiring. From 1915 until 1919 he was engaged in engineering department of the Western Electric Company, and in the latter year became a member of the engineering staff of the American Telephone and Telegraph Company. Five years later he was made equipment and building engineer. In 1929 General Harrison was appointed plant engineer with broadened responsibilities covering the general direction of the engineering, design, and layout of all phases of the Bell system plant. In 1933 he was elected vice-president in charge of operations of the Bell Telephone Company of Pennsylvania and the Diamond State Telephone Company of Delaware with headquarters in Philadelphia, Pa. In 1937 he was appointed assistant vice-president, department of operation and engineering, American Telephone and Telegraph Company. General Harrison is a past president (1937–38) of the Institute,

W. H. Harrison

was a member of the board of directors (1935–40), and has served on many AIEE committees including the following: technical program, 1929–36, chairman, 1931–33; publication, 1931–33; communication, 1935–36; award of Institute prizes, 1931–34, chairman 1931–33; co-ordination of Institute activities, 1931–33, and executive, 1936–37.

George W. Garman (A '38, M '43) control division, General Electric Company, Schenectady, N. Y., has been appointed 1945–46 chairman of the AIEE committee on electric welding. Mr. Garman was born in South Bend, Ind., in 1903, and was graduated from the University of Washington with a bachelor-of-science degree in electrical engineering in 1926, and a master-of-science degree from Union College in 1933. He started in the test department of the General Electric Company and has been with the company since that year. For an interval prior to 1940 he spent part of his time in the electronics department working on the design and development of various electronic control equipment, and with the voltage-regulator engineering division, on the design and development of various electronic voltage regulators. Subsequently, he was transferred to the industrial control engineering division where he was engaged in the design and development of electronic motor controls and resistance-welding controls. He holds 24 patents covering equipments of this type. Since 1940 he has been in the control division and has been responsible for the sale and application of electronic resistance-welding controls. Mr. Garman is a member of the American Welding Society, and a member of several of its committees. He was a member of the American Standards Association war standard committee *C*-52, and chairman of the American Standards Association war standard subcommittee *C*-52.4 and *C*-52.5.

James De Kiep (M '43) is now chief engineer in charge of electrical and mechanical design and development of the Electric Machinery Manufacturing Company, Minneapolis, Minn. As stated previously (*EE, Nov '45, p 415*) he was formerly manager of the a-c motor engineering department of the Westinghouse Electric Corporation, East Pittsburgh, Pa.

J. A. Potts (A '25, M '36) general engineer, executive department, Wisconsin Electric Power Company, Milwaukee, has been elected 1945–46 president of the Engineers' Society of Milwaukee. Mr. Potts was graduated from the University of Wisconsin with a bachelor-of-science degree in electrical engineering. He was associated with Wisconsin utilities for many years and was chairman, Milwaukee Section, AIEE, 1936–37, and that Section's secretary, 1933–34. **V. R. Tate** (A '28, M '38) vice-president, secretary and attorney, Perfex Corporation, Milwaukee, was elected a director. He was graduated from the Milwaukee School of Engineering with the degree of bachelor of science in electrical engineering in 1927. After a period of service with Milwaukee

G. W. Garman

Engineering and Manufacturing Company, Radio Corporation of America, New York, N. Y., Time-O-Stat Controls Company Elkhart, Ind., and Minneapolis-Honeywell Regulator Company, Minneapolis, Minn. He became associated with the Perfex Corporation in 1934.

W. C. Kalb (A '12, F '40) formerly commercial engineer, sales department, National Carbon Company, Cleveland, Ohio, is now manager, brush-service engineering department of the same company. Mr. Kalb was born in Ohio, and was graduated from Ohio State University with the degree of mechanical engineer in electrical engineering. He entered the employ of the National Carbon Company as electrical engineer in 1907, and returned to it in 1911 after a short period with Dunlap Engineering Company, Columbus, Ohio, as general superintendent. In 1913 he was made sales engineer of the National Carbon Company. Six years later he joined the Corliss Carbon Company, Bradford, Pa., as managing engineer and when the company was purchased by the National Carbon Company, Mr. Kalb remained as superintendent of the Corliss plant. He has been commercial engineer since 1940. He holds various patents on brushes and has written many technical articles. Mr. Kalb has been very active in AIEE affairs and has held membership on many committees. They include the following: industrial and domestic power, 1918–22; electrochemistry and electrometallurgy, 1931–34 (chairman 1932–34) and 1944–45; technical program, 1932–34, 1943–45, and Standards, 1943–45.

L. C. F. Horle (A '20, F '35) radio consulting engineer, New York, N. Y., has been made chief engineer, engineering department Radio Manufacturers Association, Washington, D. C. Mr. Horle is a graduate of the Stevens Institute of Technology, Hoboken, N. J., and from 1914 until 1916 was a member of the institute faculty. From 1916 to 1917 he was employed by the Public Service Corporation of New Jersey, Newark. Later positions were with the radio laboratory of the Navy Yard, Washington, D. C.; the DeForest Radio Telephone and Telegraph Company, New York, N. Y.; and the National Bureau of Standards, Washington. Mr. Horle became a consulting engineer in 1932.

H. J. Reich (A '32, M '43) formerly special research associate, radio-research laboratory, Harvard University, Cambridge, Mass., has been appointed professor of electrical engineering, Yale University, New Haven, Conn., effective January 1, 1946. Doctor Reich was born on Staten Island, N. Y., October 25, 1900, and received a mechanical-engineer degree from Cornell University in 1924, and a doctor-of-philosophy degree in physics in 1929. After serving as an instructor of physics 1924–29 at Cornell University, he became assistant professor of electrical engineering at the University of Illinois, Urbana, and later professor of electrical engineering. On January 1, 1944, he was granted a leave of absence to join the staff of the radio-research laboratory at Harvard University. He is the author of several textbooks and some 40 technical papers covering electron tubes, tube circuits, and related subjects. He is past chairman (1936–37) of the Urbana Section, AIEE. Doctor Reich is also a senior member of the Institute of Radio Engineers, a member of American Physical Society, American Association for the Advancement of Science, and Society for the Promotion of Engineering Education.

E. U. Condon (M '44) formerly associate director of research, Westinghouse Electric Corporation, East Pittsburgh, Pa., has been appointed in the capacity of a director of the National Bureau of Standards, Washington, D. C. Doctor Condon was graduated from the University of California with a bachelor-of-arts degree in 1924 and a doctor-of-philosophy degree in 1926. From 1928 to 1937 he was associate professor of physics Princeton (N. J.) University and while there wrote a number of papers and two books on quantum mechanics and the theory of atomic spectra. In 1937 he became affiliated with the research laboratories of the Westinghouse company, as associate director. In this capacity he has had charge of fundamental research including the microwave radio and radar program. From 1940 to 1943 Doctor Condon was chairman of a company committee on radar which had the responsibility of building up the research and development program of the company.

B. F. DeLanty (A '21, M '34) former general manager and chief engineer, Pasadena (Calif.) Municipal Light and Power Department, has retired. Mr. DeLanty was born in New Ungeness, Wash., and was educated at Whitworth College. In 1899 he became identified with the Prescott (Ariz.) Electric Company remaining until 1907 when he accepted a position with the City of Pasadena as superintendent of construction for the Light and Power Department. He subsequently became general manager and chief electrical engineer. **E. L. Bettannier** (A '11, M '26) formerly chief electrical engineer, and assistant general manager has been named general manager and chief engineer. Mr. Bettannier was born in Corning, Ia., and was educated at Throop College, now the California Institute of Technology, and the Van Der Naillen School of Engineering. In 1909 he joined the Pacific Light and Power Company, Los Angeles, Calif., but a short time later was employed by the Municipal Light and Power Department, City of Pasadena. Subsequently, he became junior electrical engineer.

P. H. Crago (M '43) railroad representative, general commercial department, Federal Telephone and Radio Corporation, Newark, N. J., has been made supervisor of the New York, N. Y., branch of Wilmotte Laboratory, Inc., Washington, D. C., which provides industrialists with engineering services. Mr. Crago was graduated from the Carnegie Institute of Technology with a bachelor-of-science degree in physics in 1922. For three years he was employed by the Nachod Signal Company, Louisville, Ky., and in 1925 became associated with the Union Switch and Signal Company, Swissvale, Pa. **G. C. Engel** (A '41) formerly production manager of General Electronics, Inc., and manager of the laboratory of General Time Instruments Corporation, New York, N. Y., will be associated with Mr. Crago. Mr. Engel was graduated from Stevens Institute of Technology in 1927 as mechanical engineer. In 1927 he joined the Bell Telephone Laboratories, New York, N. Y., and later was employed by Thomas A. Edison, Inc., West Orange, N. J., and the Sylvania Corporation, Clifton, N. J.

Frederick Krug (A '17, F '36) general manager and director, Montreal (Quebec, Canada) Engineering Company, Ltd., was recently elected in addition to his present office a director of the International Power Company, Ltd., and vice-president and director of the Monterey Railway, Light and Power Company, southern properties of the Montreal Engineering Company. Mr. Krug studied at Cooper Union and the New Mexico School of Mines. He has been identified with several companies and at one time was assistant superintendent, electrical department, New York and Honduras Rosario Mining Company, San Juancito, Honduras, Central America, and superintendent of power production for the Puerto Rico Railway, Light and Power Company, San Juan.

R. D. Birge, Jr. (A '39) formerly application engineer, The Louis Allis Company, Philadelphia, Pa., has been appointed Detroit, Mich., representative, storage-battery division, Philco Corporation. Mr. Birge was graduated from Purdue University in electrical engineering in 1938. He has been associated with the Louis Allis Company in Detroit and Philadelphia for four years.

E. B. Curdts (A '25, M '29) superintendent, substation maintenance, Narragansett Electric Company, Providence, R. I., has joined the staff of James G. Biddle Company, Philadelphia, Pa., as application engineer. Mr. Curdts became associated with the Providence company 16 years ago. Prior to that he served the Virginia Railway and Power Company, Petersburg, and its successor, the Virginia Electric Power Company.

C. O. Bickelhaupt (M '22, F '28) vice-president, American Telephone and Telegraph Company, New York, N. Y., and recently brigadier general, Army of the United States, has been elected to the additional office of secretary of the afore-mentioned organization. General Bickelhaupt became associated with the American Telephone and Telegraph Company in 1911 when he was employed as toll-traffic engineer and commercial engineer. In 1930, after an interval with the Cumberland Telephone Company and the Southern Bell Telephone and Telegraph Company, Atlanta, Ga., he returned to the American Telephone and Telegraph Company as assistant vice-president and later was named vice-president. In 1941 he was called to active duty with the Army and in 1944 was promoted to the rank of brigadier general.

C. L. Davis (A '29, M '37) formerly manager, Washington, D. C., office, patent department, Radio Corporation of America, now is engaged in the general practice of law in Washington and will continue to specialize in matters relating to patents and research. Mr. Davis attended the Iowa State College, George Washington University, and National University. He holds the degrees of bachelor and master of laws. From 1923 to 1925 he served in the Signal Corps, United States Army, as radio engineer. During the next three years he was radio engineer and part owner of radiobroadcasting station WJAF, Detroit, Mich. Before organizing the Washington office for the Radio Corporation of America he was instructor in radio at the School of Engineering, Milwaukee, Wis.

J. B. Coleman (A '25) chief engineer, special apparatus engineering division, Victor division, Radio Corporation of America, has been appointed assistant director of engineering for the Victor division with offices at Camden, N. J. Mr. Coleman was educated at the Carnegie Institute of Technology. He was employed by that institute as radio instructor, and later became associated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He joined the Radio Corporation of America in 1930.

OBITUARY • • • • •

Leslie LaMonde Dyer (A '10, M '37) for 37 years prior to his retirement in 1939, affiliated with the Southern California Edison Company, Ltd., and its predecessors, died August 24, 1945. Born November 22, 1878, in Abbot, Ia., Mr. Dyer first became affiliated with the San Gabriel Electric Company, Los Angeles, Calif., as assistant dynamo tender in September 1902 and later became switchboard operator at the company's Third Street substation. Subsequently he became chief operator at the Redondo Steam Plant, and in 1914 was made superintendent of the company's southern division. When in 1917 the systems of the Pacific Light and Power Company and the then Edison Electric Company were merged, Mr. Dyer was appointed assistant superintendent of transmission of the consolidated organization which was known as the Southern California Edison Company. Five years later he became superintendent of substation operation for the entire Edison system, a position which

be held until his retirement in 1939. A Navy Spanish-American war veteran, Mr. Dyer was unable to restrain himself in retirement under the pressing manpower demands of World War II, and went on active duty in July 1941 as a civilian electrical inspector for the United States Navy at a Terminal Island (Calif.) shipyard, where he remained until July 1944, when failing health overtook him.

Jesse Robert Lovejoy (A '91, M '94, F '13) honorary vice-president, General Electric Company, Schenectady, N. Y., died October 31, 1945. Mr. Lovejoy was born November 10, 1863, at Columbus, Ohio, and was graduated from Ohio State University in 1884 with the degree of bachelor of science. He began work in the Thomson-Houston Electric Company at Lynn, Mass., in 1886 and the following year was appointed construction superintendent. With the formation of the General Electric Company in 1892 Mr. Lovejoy was appointed manager of the supply department. In 1900 he was placed in charge of the railway and lighting department, and seven years later became general sales manager when he was elected a vice-president. As vice-president in charge of sales he was active in the development of business throughout the company's foreign department. Subsequently, he was elected president of the Mexican General Electric Company, the South African General Electric Company, the Australian General Electric Company and the South American General Electric Company. In 1928 he was elected an honorary vice-president of General Electric Company.

Bertrand Perry Rowe (A '03, M '05, F '13) retired, Westinghouse Electric Corporation, East Pittsburgh, Pa., died September 21, 1945. He was born in Ithaca, N. Y., September 2, 1868, and was graduated from Cornell University in 1892 with the degree of mechanical engineer in electrical engineering. Early in his career he worked for the Short Electric Railways Company, Cleveland, Ohio, and for a short period was with the General Electric Company, New York, N. Y. Later he was associated with the Creston Colorada Mining and Milling Company, Sonora, Mexico, and then accepted a position on the engineering staff of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He then served as general engineer and acted as a consulting engineer. During World War I he was assigned to remain at the Westinghouse works to prepare plans, specifications, estimates and projects and for the Government plants in Navy yards and munition plants. For five years before his retirement at the age of 65 he served as consulting engineer for the Los Angeles, (Calif.) district under the engineering department of that district. Mr. Rowe was a pioneer in the designing and installation of power plants, among them the Ontario Power Company, Niagara Falls, N. Y.

William Russell Cone Corson (A '93) chairman, board of directors, Hartford (Conn.) Steam Boiler Inspection and Insurance Company, died October 2, 1945. Mr. Corson was born in New York, N. Y., in 1870 and was graduated from Yale University with the degree of bachelor of arts in 1891. Shortly after graduation he entered the shops of the Eddy Electrical Manufacturing Company, Windsor, Conn., later becoming assistant electrical engineer, superintendent, and secretary. In 1902 he established a consulting office in Hartford, and five years later joined the Hartford Steam Boiler Inspection and Insurance Company as assistant engineer. In 1909 he was appointed assistant secretary, and secretary and treasurer in 1916. In 1921 he was made vice-president and treasurer and in 1927 he was elected president. He was elected chairman of the board in 1942.

Arthur A. Bolsterli (A '23, M '32) research engineer, Moloney Electric Company, St. Louis, Mo., died September 25, 1945. Mr. Bolsterli was born in Lucerne, Switzerland, in 1892, and was graduated in 1918 from the Zurick Polytechnic Institute with degrees in electrical and mechanical engineering. He had been associated with Oerlikon Company in England; Brown Boveri, Halfely Company; A. G. and Micafil in Switzerland; American Brown-Boveri Western Electric Company, Safety Car Heating and Lighting Company, Roller Smith Company and Moloney Electric Company in the United States. Mr. Bolsterli was the author of several technical papers. He was a member of the Institution of Electrical Engineers, England, and the Schweizerischer Elektrotechnischer Verein.

George Ellis Hutchinson (A '11, M '19) formerly chief engineer in charge of safety work, Utilities Mutual Insurance Company, New York, N. Y., died October 20, 1945 in Rochester, N. Y. Mr. Hutchinson was born in New York June 25, 1887, and was graduated from Columbia University in 1909 with the degree of electrical engineer. He was first associated with the Crocker Wheeler Company, Ampere, N. J. as draftsman, later becoming assistant engineer of the a-c design department. Later he was with the New York Edison Company. Mr. Hutchinson was with the National Carbon Company, Cleveland, Ohio, from 1920 to 1922, and in the latter year went with the Utilities Mutual Insurance Company as a safety engineer. During World War I he served as a lieutenant in the United States Navy.

MEMBERSHIP . . .

Recommended for Transfer

The board of examiners, at its meeting of November 15, 1945, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the secretary of the Institute.

To Grade of Fellow

Eastham, M., chief engr., General Radio Co., Cambridge, Mass.
Hamdi, A. F., director general, dept. of elec. research, Ministry of Public Works, Ankara, Turkey.
Larsen, E. U., asst. chief engr., Cutler-Hammer, Inc., Milwaukee, Wis.
Ryan, F. M., radio engr., American Tel. & Tel. Co., New York, N. Y.
Scholz, H. J., supervisory engr., Commonwealth & Southern Corp., Birmingham, Ala.
Shanklin, G. B., engr. in charge, cable div., General Electric Co., Schenectady, N. Y.
Stevenson, J. R., director, elec. div., Memphis Lt., Gas & Water Div., Memphis, Tenn.
7 to grade of Fellow

To Grade of Member

Blomqvist, E. A., asst., administration applied physics lab., Johns Hopkins Univ., Silver Spring, Md.
Bork, M. J., Jr., engr., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
Brown, E. E., engr., Philadelphia Electric Co., Philadelphia, Pa.
Davis, E. R., industrial pr. engr., Duke Power Co., Charlotte, N. C.
Davis, S. W., div. engr., Southwestern Public Service Co., Amarillo, Tex.
Dexter, H. W., Jr., director, pr. & steam utilization div., Duquesne Lt. & Allegheny County Steam Heating Cos., Pittsburgh, Pa.
Elmer, W. B., section engr., Westinghouse Electric Corp., Cleveland, O.
Ellestad, I. M., trans. engr., Northwestern Bell Tel Co., Omaha, Nebr.
Frakes, J. H., elec. engr., Westinghouse Electric Corp., E. Pittsburgh, Pa.
Franks, S. T., elec. engr., Canadian & General Finance Co., Toronto, Ont., Can.
Grosser, G. E., switchgear specialist, Westinghouse Electric Corp., Philadelphia, Pa.
Keeler, O. E., switchgear engr., Westinghouse Electric Corp., San Francisco, Calif.
MacCallum, A. F., maint. engr., Westinghouse Electric Corp., Houston, Tex.
McDonough, M. E., ship elect. foreman, Federal Shipbuilding & Dry Dock Co., Port Newark, N. J.
Michener, H. P., Jr., asst. elec. engr., Underwriters' Laboratories, Inc., New York, N. Y.
Peatfield, R. R., supt., elec. engg. dept., Clinton Engineer Works, Tennessee Eastman Corp., Knoxville, Tenn.
Rankin, M. B., supervisory engr., Ohio Edison Co., Akron, O.
Schaefer, L. P., elec. engr., Naval Ordnance Lab., Navy Yard, Washington, D. C.
Smith, M. J., instructor in elec. engg., Rice Institute, Houston, Tex.
Trekell, H. E., asst. des. engr., meter div., General Electric Co., West Lynn, Mass.
Van Kleeck, R. E., sr. engr., Philadelphia Electric Co., Philadelphia, Pa.
York, J. W., design engr., motor div., Westinghouse Electric Corp., E. Pittsburgh, Pa.
22 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the secretary before January 15, 1946, or March 15, 1946, if the applicant resides outside of the United States or Canada.

To Grade of Member

Adams, E. F. (Re-election), Weston Elect. Inst. Corp., Newark, N. J.
Brooks, H. (Re-election), Westinghouse Elec. Corp., East Pittsburgh, Pa.
Brown, H. H., Toulmin & Toulmin, Dayton, Ohio
Buchanan, J. C., Tennessee Valley Authority, Knoxville
Burney, C. W., The Austin Co., Cleveland, Ohio
Carter, W. R., Electric Machinery Mfg. Co., Minneapolis, Minn.
Cheng, C. Y., National Resources Comm. of China, Chungking, China
Crego, V., Republic Steel Corp., Northern Ore Mines, Duluth, Minn.
Cuthill, H. W. (Re-election), Consolidated Edison Co. of N. Y., New York, N. Y.
Debes, C. N., Charles N. Debes & Asso., Rockford, Ill.
DeGuise, Y., Quebec Hydro, Montreal, Que., Can.
Elam, E. R., Kiefer Electric Co., Peoria, Ill.
Fingerman, S., Jr. (Re-election), U. S. Bureau of Reclamation, Denver, Colo.
Forostovsky, O. J., Western Electric Co., Kearny, N. J.
Fuchs, N. Y., Westinghouse Elec. Int'l, New York, N. Y.
Gilmore, H. S., Laramore & Douglass, Inc., Chicago, Ill.
Hanson, A. N., Western Electric Co., Chicago, Ill.
Hotchkiss, G. (Re-election), Western Union Telegraph Co., New York, N. Y.
Irvine, T. F. (Re-election), Federal Tel. & Radio Corp., Newark, N. J.
Jollin, W. M., Public Service Co. of Northern Ill., Maywood, Ill.
Kern, B. B., Penna. Power & Light Co., Shenandoah, Pa.
Madgett, J. P., Jr., Central Nebr. Pub. Pr. & Irrig. Dist., Hastings, Nebr.
Mathews, L. E. (Re-election), Bureau of Reclamation, Salt Lake City, Utah
Mead, R. S., Transcontinental & Western Air, Inc., Kansas City, Mo.
Naylor, J. T., Associated Telephone Co., Ltd., Santa Monica, Calif.
Nelsen, M. G., Guardian Elec. Mfg. Co., Chicago, Ill.
Nichols, C. R., Lt. Col., U. S. Military Academy, West Point, N. Y.
Nickerson, C. W. (Re-election), Broadway Maintenance Corp., Long Island City, N. Y.
Parker, J. P., McLellan & Partners, London, England
Payne, J. B., H. N. Roberts Consulting Engr., Lubbock, Tex.
Peters, A. W., Shawinigan Water & Power Co., Three Rivers, Que., Can.
Peterson, E. S., Automatic Elec. Co., Chicago, Ill.
Polk, O. H., Lt. Cdr., USNR (Re-election), U. S. Naval Academy, Annapolis, Md.
Price, E. P., Price & Hawk, Lubbock, Tex.
Reynolds, J. N., Crescent Insulated Wire & Cable Co., Trenton, N. J.
Ryan, J. E., General Electric Co., Schenectady, N. Y.
Salmon, J. T., Commonwealth Edison Co., Chicago, Ill.

Schairer, E. G., Armstrong Cork Co., Lancaster, Pa.
Shevelenko, D., G. M. Laboratories, Inc., Chicago, Ill.
Stafford, J. K. (Re-election), General Electric Co., Pittsfield, Mass.
Tuttle, A. S., International Nickel Co. of Canada, Ltd., Toronto, Ont., Canada
Van Nostrand, E. S., Southwestern Public Service Co., Amarillo, Tex.
Waggoner, W. R., The Commonwealth & Southern Corp., Birmingham, Ala.
Weiss, O., Charles M. Terry Pty. Ltd., Sydney, N.S.W., Australia

44 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Bacon, R. E., Holyoke Water Pr. Co., Holyoke, Mass.
Cowpal, E. T., Central N. Y. Power Corp., Syracuse, N. Y.
Dana, D. W., General Electric Co., Lynn, Mass.
Fisk, D. B., General Electric Co., West Lynn, Mass.
Fiske, R. T., Westinghouse Electric Corp., Boston, Mass.
Hrabchak, E. W., General Electric Co., New Haven, Conn.
Johnson, C. L. (Re-election), Hart Mfg. Co., Hartford, Conn.
Kihlstrom, H. C., Westinghouse Elec. Corp., Buffalo, N. Y.
Lemeshe, J. W., General Elec. Co., New Haven, Conn.
Lewis, J. B., Jr., General Elec. Co., Bridgeport, Conn.
Murdock, H. W., General Elec. Co., Boston, Mass.
Perkins, S. D., Westinghouse Electric Corp., Providence, R. I.
Peterson, W. C., General Electric Co., Pittsfield, Mass.
Pierce, G. A., Hartford Steam Boiler Inspection & Insurance Co., Boston, Mass.
Quinn, Q. Q., Conn. Light & Power Co., Waterbury, Conn.
Reynolds, H. E., Eastman Kodak Co., Rochester, N. Y.
Russell, J. S., Jr., General Electric Co., Schenectady, N. Y.
Smith, J. C., General Elec. Co., Buffalo, N. Y.
Smith, M. E., Oakes Electrical Companies, Holyoke, Mass.
Speed, D. E., Mass. Inst. of Tech., Cambridge, Mass.
Swenson, C. A., Curtiss-Wright Research Lab., Buffalo, N. Y.
Tanner, H. A. J., Submarine Signal Co., Boston, Mass.
Wells, W. H. (Re-election), The Connecticut Light & Power Co., Waterbury, Conn.
Williams, M., Rome Cable Corp., Rome, N. Y.
Wilson, P. H., General Elec. Co., Lynn, Mass.
Yoffe, B., U. S. Naval Drydock, South Boston, Mass.

2. Middle Eastern

Adams, W. D., USAAF, Wright Field, Dayton, Ohio
Batchelor, A. J. (Re-election), Toledo Edison Co., Toledo, Ohio
Behm, H. J., Delco Products Div., GMC, Dayton, Ohio
Center, C. E., Westinghouse Elec. Corp., East Pittsburgh, Pa.
Dennis, R. A., Dravo Corp., Pittsburgh, Pa.
Durborow, I. N., Jr., Atlas Powder Co., Wilmington, Del.
Fox, F. M., Reliance Elec. & Engr. Co., Cleveland, Ohio
Fuller, J. (Re-election), Westinghouse Elec. Corp., East Pittsburgh, Pa.
Gemmell, W. H., Philadelphia Electric Co., Philadelphia, Pa.
Gilbert, H. B., Cates & Shepard, Philadelphia, Pa.
Griffin, H. C., Pa. Power & Light Co., Harwood Mines, Pa.
Hanna, E. E., Imperial Electric Co., Akron, Ohio
Hensler, J. F., The Electric Storage Battery Co., Pittsburgh, Pa.
Hess, F. P., Pennsylvania Electric Co., Philadelphia, Pa.
Holdman, M., Ens., USNR, Naval Research Lab., Washington, D. C.
Kleinbach, W. S., Philadelphia Electric Co., Philadelphia, Pa.
Kuhar, W. A., Roller-Smith Co., Allentown, Pa.
McIntyre, R., General Electric Co., Erie, Pa.
Neduzner, W. J. (Re-election), Philadelphia Elec. Co., Philadelphia, Pa.
Perry, P. B., Cleveland Electric Illuminating Co., Cleveland, Ohio
Rickman, A. E., C. Ernst, Inc., Washington, D. C.
Rile, W. S., Bell Telephone Co. of Pa., Philadelphia, Pa.
Ryan, E. J., Philadelphia Elec. Co., Philadelphia, Pa.
Schommer, A. H., H. Fletcher Brown Vocational High School, Wilmington, Del.
Sckerl, A. M., U. S. Engineer Office, Cincinnati, Ohio
Sharrow, W. H., Standard Gas Equip. Corp., Baltimore, Md.
Shugars, J. G., Mutual Boiler Insurance Co. of Boston, Philadelphia, Pa.
Small, R. W., Philadelphia Electric Co., Philadelphia, Pa.
Thomas, C. C. (Re-election), Cincinnati Gas & Elec. Co., Cincinnati, Ohio
Wagner, H. A., Reliance Elec. Engineering, Cleveland, Ohio
Weaver, D. F., Jr., Potomac Electric Power Co., Washington, D. C.
Williams, J. R., Naval Research Lab., Washington, D. C.
Witte, F. R., U. S. Coast Guard Hqs., Washington, D. C.
Yerger, J. F., Lehigh Valley Railroad, Bethlehem, Pa.
Zimmerman, E. W., Reliance Electric & Engineering, Cleveland, Ohio

3. New York City

Arany, D. M., Federal Telephone & Radio Corp., Newark, N. J.
Ayer, G. R., Western Electric Co., Inc., New York, N. Y.
Baird, R. M., Jr., Westinghouse Electric Corp., Newark, N. J.
Boudtron, R. C., Westinghouse Elec. Int'l. Co., New York, N. Y.
Boyce, E. W. (Re-election), Smith Hinchman & Grylls, Inc., New York, N. Y.
Brennan, T. J., Western Electric Co., New York, N. Y.
Denike, A. R., J. G. White Engineering Corp., New York, N. Y.
Digiovanno, J. V. M., The Lionel Corp., Irvington, N. J.
Faber, S. S., Liquidometer Co., New York, N. Y.
Greene, R. B., American Transformer Co., Newark, N. J.
Kelly, T., War Dept., Transportation Corps, New York, N. Y.
Kirsch, M. J. (Re-election), Federal Engineering Co., New York, N. Y.
Kleinberger, R. C. (Re-election), Radio Receptor Co., New York, N. Y.
Magno, H. T., Federal Tel. & Radio Corp., New York, N. Y.
Mushnitzky, D., 42 North Broadway, Long Branch, N. J.
Panuzis, J. L., Underwriters' Laboratories, Inc., New York, N. Y.
Pearsall, T. M., Jr., Bell Tel. Labs., Inc., New York, N. Y.
Reed, F. C., Jr., New York Telephone Co., Brooklyn, N. Y.
Sternbergen, E. G., Todd Shipyards Corp., New York, N. Y.
Stern, R. M., Bol, Ltd., New York, N. Y.
Swingle, D. M., Lt., Evans Signal Lab., SCEL, Belmar, N. J.
Ulm, E. H., Sylvania Electric Products, Inc., New York, N. Y.
Varga, G., U. S. Navy Yard, Brooklyn, N. Y.

4. Southern

Barron, O. E., Jr., Robbins & Myers, Inc., New Orleans, La.
Craven, E. H., Evans Electrical Construction Co., Pascagoula, Miss.
Crossley, W. W., Cities Service Refinery, Lake Charles, La.
Dewender, H. J., The Kellex Corp., Clinton Engineer Works, Knoxville, Tenn.
Dishner, W. D., Tennessee Eastman Corp., Kingsport, Tenn.
Early, C. H., Alabama Power Co., Birmingham, Ala.
Erickson, J. V., The Kellex Corp., Clinton Engineer Works, Knoxville, Tenn.
Ford, R. A., U. S. Waterways Experiment Station, Vicksburg, Miss.
Hardy, S. H., Shaw Hardy, Miami, Fla.
Hill, G. H., Cities Service Refinery, Lake Charles, La.
McCord, C., Tennessee Valley Authority, Knoxville, Tenn.
Medcrie, W. P., General Elec. Co., Richmond, Va.
Oldham, G. B., Godat & Heft, New Orleans, La.
Stone, W. T., Norfolk Navy Yard, Portsmouth, Va.
Trimble, C. R. (Re-election), C. R. Trimble Co., Charlotte, N. C.

5. Great Lakes

Blytheman, G. C., Fisher Body Ternstedt Div., Detroit, Mich.
Cress, R. C., Gould Storage Battery Corp., Chicago, Ill.
Crist, J. U., Indiana & Michigan Electric Co., Elkhart, Ind.
Enyart, R. B., Goodman Mfg. Co., Chicago, Ill.
Froland, O., Kyle Corp., South Milwaukee, Wis.
Greenwood, G. E., The Detroit Edison Co., Detroit, Mich.
Hermelin, S. A. E., Automatic Elec. Co., Chicago, Ill.
Hinds, S. C., A. C. Spark Plug, Flint, Mich.
Hufnagel, F. C. (Re-election), Power Equipment Co., Detroit, Mich.
Larson, L. O., Western Electric Co., Chicago, Ill.
Larson, R. W., Wyman Gordon Co., Harvey, Ill.
Lenard, R. G., 1640 Greenleaf Ave., Chicago 26, Ill.
Livingston, E. E., Commonwealth Edison Co., Chicago, Ill.
Long, A. P., Wyman Gordon Co., Harvey, Ill.
McHaffie, M. (Miss), Harper J. Ransburg Co., Clayton, Ind.
Pavlenko, V. Z., Caterpillar Tractor Co., Peoria, Ill.
Rembusch, J. F., Public Service Co. of Northern Ill., Chicago, Ill.
Rohde, C. H., Defoe Shipbuilding Co., Bay City, Mich.
Rutishauser, M. H., Clymer Engineering & Sales, Inc., Milwaukee, Wis.
Salatin, J., Delco-Remy Div., General Motors, Anderson, Ind.
Scobell, R. H., Guardian Elec. Mfg. Co., Chicago, Ill.
Slaybaugh, R. D., Consumers Power Co., Jackson, Mich.
Steele, A. D., Minnesota Mining & Mfg. Co., St. Paul, Minn.
Wartzok, D. F., Indiana Service Corp., Fort Wayne, Ind.
White, T. J., Kyle Corporation, So. Milwaukee, Wis.
Wieschahn, H. F., U. S. Rubber Co., Detroit, Mich.

6. North Central

Vollmer, M. F., Bureau of Reclamation, Denver, Colo.

7. South West

Battern, R. W., Pillsbury Mills, Inc., Enid, Okla.
Chilton, J. M., Texas A & M College, College Station, Tex.
Chunn, C. B., Southwestern Public Service Co., Amarillo, Texas
Claughton, J. C., Jr., Southwestern Public Service Co., Amarillo, Texas
Claybaugh, H. W., U. S. Engineer Office, Little Rock, Ark.
Dansby, W. W., Sr., Texas Electric Service Co., Ft. Worth, Texas
Depew, T. S., Standard Measuring & Equipment Co., Enid, Okla.
Frank, S. B., James R. Kearney Corp., St. Louis, Mo.
Groeteke, E. A., B-I Electric Mfg. Co., St. Louis, Mo.
Keller, T. T., Kansas Gas & Electric Co., Wichita, Kan.
Loughridge, R. F., Elevator Service Co., Ft. Worth, Texas
Macune, C. W., Consolidated Vultee Aircraft Corp., Ft. Worth, Texas
Miller, J. A., Southwestern Public Service Co., Plainview, Tex.
Northup, J. R., Oklahoma Gas & Electric Co., Enid, Okla.
Roberts, H. N., 2415—20th St., Lubbock, Texas
Smith, H. J., Southern Methodist University, Dallas, Tex.
Sterrett, P. S., Southwestern Public Service Co., Clovis, N. M.
Wallar, O. W., Fagan Electric Co., Little Rock, Ark.
Walvoord, R. H., Allis-Chalmers Mfg. Co., Amarillo, Texas
Waters, W. F., Southwestern Bell Telephone Co., Dallas, Tex.
Wayland, J. R., Southwestern Public Service Co., Plainview, Texas
Williams, W. L. C., General Electric Co., Oklahoma City, Okla.

8. Pacific

Bean, R. N., Lt., USNR, Degaussing Station, San Pedro, Calif.
Bettersworth, T. A., Pacific Gas & Elec. Co., San Francisco, Calif.
Bowser, W. A., Dept. of Water & Power, Los Angeles, Calif.
Denton, W. T., Dept. of Water & Power, Los Angeles Calif.
Fraser, R. J., 539 44th Ave., San Francisco, Calif.
Hokden, A. F., Pacific Gas & Elec. Co., San Francisco, Calif.
Hollingsworth, H. P., Naval Air Station, San Diego, Calif.
Humphrey, W. E., Dept. of Water & Power, Los Angeles, Calif.
Ingalls, R. E., C. E. Ingalls, San Francisco, Calif.
Kendall, F. I. S., Southern Calif. Tel. Co., Los Angeles, Calif.
Kostainek, E. L., General Electric Co., San Francisco, Calif.
McCarvel, J. M., Westinghouse Elec. Corp., Los Angeles, Calif.
Moore, R. M., Southern Calif. Tel. Co., Los Angeles, Calif.
Retherford, H. N., Firestone Tire & Rubber Co., Los Angeles, Calif.
Shinn, E. S., Johannessen & Girand, Phoenix, Ariz.
Stirmus, W. F. J., Moore Dry Dock Co., Oakland, Calif.
Welch, T. R., United Aircraft Products, Inc., Los Angeles, Calif.
Younger, U. E., U. S. Navy, Research & Development Section, Pasadena, Calif.

9. North West

Anslow, L. E., Sr., Portland General Elec. Co., Portland, Oreg.
Eagan, F. E., R. W. Beck & Associates, Seattle, Wash.
Gill, B. J., Tisling & Powell, Spokane, Wash.

10. Canada

Ayers, R. E., Elec. Sub Lieut., RCNVR, H.M.C.S. Stadacona, Halifax, N. S., Can.
Haskett, G. P., Westdale Electric, Toronto, Ont., Can.
Hausch, R. C., B. C. Electric Railway Co., Vancouver, B. C., Can.
Little, H. W., Northern Elec. Co., Lt., Montreal, P. Q., Can.
Maxwell, H. H., Bell Telephone Co. of Canada, Toronto, Ont., Can.
Peacock, R. F., Canadian General Electric Co., Toronto, Ont., Can.
Rose, P. E., Canadian General Elec. Co., Ltd., Montreal, Que., Can.
Taylor, D. E., Elec. Lt., R.C.N., Naval Service Headquarters, Ottawa, Ont., Can.
Wilkind, C. A., Amalgamated Electric Corp., Ltd., Toronto, Ont., Can.
Williams, J. W., Northern Elec. Co., Ltd., Montreal, Que., Can.

Elsewhere

Chaturvedi, A. C., P. W. D., Lucknow, U. P., India
Dayal, D., Govt. Ordnance Factory, Khamaria, Jubbulpore, C. P., India
Gault, F. E., U. S. Engineers, CPBC, Fort Armstrong, Honolulu, T. H.
Hamm, A., New Consolidated Goldfields, Johannesburg, South Africa
Ingalsbe, W. E., Construction Service, CPBC, Fort Armstrong, Honolulu, T. H.
Kamel, G., Edfu Power Station, Atwani, Egypt
Leech, W. P., The English Elec. Co., Ltd., Stafford, Eng.
Llanedon, P. H., c/o Constructora Nacional de Maquinaria Electrica, Madrid, Spain
Narayana Rao, K. L. R., Sri Jayachamarajendra Occupational Institute, Bangalore, S. India
Ramun, H. (Re-election), Elektriciteits-Aktieselskabet A E G, Oslo, Norway
Row, V. L. N., E. I. Rly Technical School, Jamalpur, India
Sibberry, L. A., Bridgend Urban Dist. Council Electricity Dept., Bridgend, Glam, S. Wales
Srivastava, A. S., Bairampur Estate Electric Supply Dept., Bairampur, Distt. Gonda U. P., India

Total to grade of Associate

United States and Canada, 179
Elsewhere, 13

OF CURRENT INTEREST

ECPD Plans Re-examination of Engineering Schools

Plans for the re-examination of the curricula of engineering schools previously accredited by the Engineers Council for Professional Development were announced at the ECPD annual meeting held in New York, N. Y., October 19-20, 1945, by the committee on engineering schools. It is contemplated that the proposed re-examination will be undertaken progressively as the schools recover from the effects of their wartime activity. Examination of the curricula of schools that already have applied to ECPD for accrediting will continue meanwhile.

Special attention is expected to be given by the committee, in its re-examination work, to those engineering schools, the graduates of which have consistently failed or made minimum grades in license examinations. Also, the accrediting of technical institutes, authorized last year, is expected to be undertaken soon.

SHORTAGE OF ENGINEERS

The apparent lack of knowledge evidenced by educational counselors at military camps and high schools concerning the serious shortage of graduate engineers, was an item of special concern to the committee on student selection and guidance, and consideration is being given as to ways and means of helping to correct that situation. With reference to this point, the committee reported that the demand for engineers appears to have reached a maximum whereas the supply is approaching a minimum, largely as the result of wartime interruption to engineering education and the failure of military policy adequately to recognize the essentiality of scientific training. The committee has written to local engineering societies requesting local activity in interesting returning veterans in engineering work or in further study of engineering subjects.

CIVIL SERVICE REQUIREMENTS

Concern was expressed by the committee on engineering schools and by the committee on professional recognition that Civil Service requirements for engineering positions in government service might be lowered under the Veterans Preference Act of 1944. Thus stimulated, ECPD adopted a resolution that "ECPD will be pleased to support the Civil Service Commission in its efforts to maintain professional standards of performance in science and engineering and to co-operate in the appointment of an advisory group to consider this problem in relation to the physical sciences, pure and applied."

UNIFORM MEMBERSHIP GRADES

The committee on professional recognition repeated a previous recommendation that the major engineering societies establish uniform membership requirements and uniform membership-grade nomenclature, and that these be limited to the following:

1. *Fellow*—an engineer of distinction.

2. *Member*—an engineer who has achieved education and experience equal to the "minimum definition" proposed by ECPD in 1933:

(a). Graduation from an approved course in engineering of four years or more in an approved school or college; a specific record of an additional four years or more of active practice in engineering work of a character satisfactory to the examining body (the examining body, in its discretion, may give credit for graduate study in counting years of active practice); and the successful passing of a written and oral examination covering technical, economic, and cultural subjects, and designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society; or alternatively

(b). Eight years or more of active practice in engineering work of a character satisfactory to the examining body, and the passing of written and oral examination designed to show knowledge and skill approximating that attained through graduation from an approved engineering course, and also examinations written and oral covering technical, economic, and cultural subjects designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society.

3. *Junior Member*—graduate of an approved school, or four years or more of satisfactory experience.

4. *Student Member*—a student pursuing the study of engineering in a recognized school under accredited curricula.

RECOMMENDATION NOT NEW

This recommendation harks back some 12 years to the committee's recommendation in the first annual report of ECPD in 1933, with the interesting contrast that the committee now recommends the fellow grade in addition to the three basic grades, and that the society membership be *limited* to these grades whereas the 1933 recommendation adopted by ECPD for submission to its constituent bodies specifically stipulated that the suggested basic grades of membership were "not intended to exclude the affiliation of other persons with any constituent society in a capacity other than the grades of membership indicated."

COMMITTEE'S 1933 PROPOSAL NOT SATISFACTORY

This proposal for standard grades of membership and common nomenclature for them has been variously studied by AIEE and other ECPD constituent bodies during the intervening 12 years, but the committee has been unable to resolve the administrative and other difficulties that would be incurred by at least some of the societies in attempting to apply the committee's proposal. For example, the great body of AIEE Associates is not at all satisfactorily accommodated by the committee's 1933 proposal, and much less so by the committee's less flexible current proposal.

In view of these and other aspects of the problem, the proposal was referred back to the committee by ECPD Council.

PROFESSIONAL ATTRIBUTES

In discussing the qualities which are believed to distinguish a professional from a nonprofessional, the committee on professional recognition recalled attention to the following list of attributes of a profession and its practitioners:

Attributes of a Profession

1. It must satisfy an indispensable and beneficial social need.

2. Its work must require the exercise of discretion and judgment and not be subject to standardization.

3. It is a type of activity conducted from a high intellectual plane.

(a). Its knowledge and skills are not common possessions of the general public; they are the result of tested research and experience, and are acquired through a special discipline of education and practice.

(b). Engineering requires a body of distinctive knowledge (science) and art (skill).

4. It must have group consciousness for the promotion of technical knowledge and professional ideals, and for rendering social services.

5. It should have legal status and must require well-formulated standards of admission.

Attributes of Professional Practitioners

1. They must have a service motive, sharing their advances in knowledge, guarding their professional integrity and ideals, and rendering gratuitous public service in addition to that engaged by clients.

2. They must recognize their obligations to society and to practitioners by living up to established and accepted codes of conduct.

3. They must assume relations of confidence and accept individual responsibility.

4. They should be members of professional groups, and they should carry their part of the responsibility of advancing professional knowledge, ideals, and practice.

The committee on professional recognition also recommended that ECPD constituent organizations study engineering salary schedules, develop a uniform code of ethics for engineers; that ECPD "urge the Civil Service Commission to make definite engineering educational requirements for entrance into engineering employment with the Federal Government."

CHAIRMAN LEE EMPHASIZES POTENTIALITIES

In re-emphasizing the opportunities which ECPD offers to the individual members of its constituent societies for social and professional contributions to the solidarity and the constructive usefulness of the engineering profession in a professional way as distinguished from specific techniques and sciences, Chairman Lee restated and drew especial attention to ECPD objectives:

"To co-ordinate and promote efforts to attain higher standards of education and practice, greater solidarity of the engineering profession, and greater effectiveness in dealing with technical, economic, and social problems. An immediate objective, now apparently practicable of attainment, is the development of a system whereby the progress of the young engineer toward professional standing can be recognized by the public, by the profession, and by the man himself, through the development of technical and other qualifications which will enable him to meet minimum professional standards.

"Through the standing (ECPD) committees, the boy who would become an engineer is found in the high school (committee on student selection and guidance), is carried through his college life (committee on engineering schools, committee on professional training), and into his junior engineering life, say up to ten years after graduation from college (committee on professional training), and thereafter throughout his engineering life (committee on professional recognition), to form a logical sequence of participation.

"The committee on student selection and guidance shall report to ECPD the means for the educational and vocational opportunities of engineers, in order that only those may seek entrance to the profession who have the high quality, aptitude, and capacity which are required of its members. To this end, the committee reports this year the continuance of the research work under Doctor W. K. Vaughn of the Carnegie Foundation, on the pre-engineering inventory whereby students entering the freshman year of our engineering colleges can be tested as to their fitness for the engineering courses. The past year has added 4,889 students tested to give a total of 13,982 tested in 25 engineering schools. This is a most important phase of our engineering activity . . . . The general characteristics of the engineering students presented in this report have significance. Preliminary study of test results indicates that many of these factors bear directly upon the success of individual students in the colleges of engineering. As we learn more about these factors and are able to relate them to student ability and accomplishment, examination techniques and guidance functions can be greatly strengthened and improved, thereby improving the whole process of engineering education. This is an opportunity open to every engineer in his local community who will give the time to work with the high schools in his territory to bring a better appreciation of the qualifications of the boy who would become an engineer.

". . . . Agencies for helping and guiding the Servicemen have been set up in localities throughout our land and local engineering groups can find plenty to do in aiding these agencies in the special guidance appropriate to the engineering field . . . and do not think, fellow engineers, that there is a surplus of engineers. There is, on the contrary, a mighty deficit. The committee estimates that the need for engineers is such that while in normal years 25,000 freshmen would enter engineering colleges, to meet present needs 65,000 freshmen would have to enter engineering colleges this year. The need for selection and guidance under these conditions is greater than ever.

ENGINEERING SCHOOLS

"The committee on engineering schools reports to ECPD the means for bringing about co-operation between the engineering profession and the engineering schools. As an intermediate step, the committee reports to the Council criteria for colleges of engineering which will insure to their graduates a sound educational foundation for the practice of engineering. In this committee is centered the accrediting activity of ECPD to give an accredited list of engineering courses recognized as standard . . . during the war years these inspections have been held to a minimum, as the committee has believed that engineering colleges could not be judged fairly while operating under war conditions. Even so, during the past three years, 26 curricula at 13 institutions were investigated, and special consideration given to 25 curricula at other institutions. With the resumption of normal activities, the normal accrediting program will be resumed.

"This year has seen the active setting up of a complete regional committee personnel, covering the entire United States . . . for the accrediting of technical-institute curricula. This includes a personnel representation of 125 engineers and educators . . . . The days to come will see the beginning of technical institute accrediting under the same guiding principles that have made collegiate accrediting an outstanding contribution of ECPD. . . . There is still much to be done and participation of members of local engineering societies interested in the work is open to those who will contribute of their time and ability to it." Negotiations with junior colleges now are under way and the prospect is that a working agreement soon will be arrived at with such colleges.

COMMITTEE ON PROFESSIONAL TRAINING

"The committee on profesional training reports to ECPD plans for the further personal and profesional development of young engineering graduates, and also of those without formal scholastic training. Here is a great opportunity for work with the young engineer as he leaves the engineering school and enters his chosen life work. A 'Manual for Junior Engineers' is in preparation under the guidance of this committee. A continuation of the upkeep of the 'Reading List for Junior Engineers' is an important objective of this committee. . . .

COMMITTEE ON PROFESSIONAL RECOGNITION

"The committee on profesional recognition reports to ECPD methods whereby those engineers who have met suitable standards may receive corresponding profesional recognition. This work is necessarily among the engineers who have advanced in the profession, and great responsibility rests with the committee in bringing into being those concepts of the engineering profession which they seek and to which their engineering spirit gives visualization. There is need here for a greater response. . . . It is to be hoped that there will be recognition from the engineers of the local engineering societies and councils of the opportunities for bringing professional recognition into being, based upon accomplishment and service . . . this will require much individual and collective time of engineers, well spent."

PARTICIPATION IN PUBLIC AFFAIRS

Commenting upon ECPD participation in the Consultative Committee on Engineering to the War Manpower Commission during the war, Mr. Lee pointed out that "we have demonstrated that where engineers are willing to give of the limitless time demanded for the progression of those activities of which they would be a part, they are granted representation and are recognized. . . . So, again, I repeat this thought: That engineers can have those representations for which they ask and those recognitions for which they aspire, but these come only as the result of hard work."

Officers elected and committee chairmen appointed at the 1945 annual meeting of the ECPD were as follows:

Chairman—Everett S. Lee, engineer of the general engineering and consulting laboratory of the General Electric Company, Schenectady, N. Y. (re-election).

Vice-chairman—James W. Parker, president, general manager, and director of The Detroit Edison Company Detroit, Mich.

Secretary—William N. Carey, secretary and executive officer of the American Society of Civil Engineers, New York, N. Y.

Assistant secretary—H. H. Henline, secretary, American Institute of Electrical Engineers, New York, N. Y.

Chairman committee on student selection and guidance—Carl J. Eckhardt, Jr., professor of mechanical engineering and superintendent of utilities, University of Texas, Austin, Tex.

Chairman committee on engineering schools—D. B. Prentice, president, Rose Polytechnic Institute, Terre Haute, Ind.

Chairman committee on profesional training—C. A. Pohl, consulting engineer, New York, N. Y.

Chairman committee on profesional recognition—N. W. Dougherty, dean of engineering, University of Tennessee, Knoxville, Tenn.

Representatives to ECPD were appointed by the constituent bodies as follows:

American Society of Civil Engineers—Scott Lilly.

American Institute of Mining and Metallurgical Engineers—A. F. Greaves-Walker (reappointment).

American Society of Mechanical Engineers—John E. Younger.

American Institute of Electrical Engineers—M. S. Coover.

Society for the Promotion of Engineering Education—D. B. Prentice (reappointment).

Engineering Institute of Canada—deGaspe' Beaubien.

American Institute of Chemical Engineers—W. T. Nichols.

National Council of State Boards of Engineering Examiners—George M. Shephard.

The ECPD executive committee for the ensuing year will include R. E. Bakenhus, ASCE; W. B. Plank, AIME; R. L. Goetzenberger, ASME; M. S. Coover, AIEE; S. D. Kirkpatrick, AIChE; H. S. Rogers, SPEE; C. R. Young, EIC; and C. C. Knipmeyer, NCSBEE, in addition to Chairman Lee, Vice-Chairman Parker, Secretary Carey, and Assistant Secretary Henline.

Microwave Radio to Augment Wire Services

A microwave radio-relay communications system with two-way voice transmission over radio links totalling 1,400 miles was demonstrated by the Bell Telephone Laboratories, New York, N. Y., October 31, 1945, over circuits between the West Street building of the New York Telephone Company, and Neshanic, N. J. Reputed to be the first microwave radio-relay system that has been used for long-distance telephony, this system employs pulse-position modulation—a form of frequency modulation which provides unusual stability of operation over great distances. All units of the system used by the armed services in the European theater of operations were supplied by the Western Electric Company, the manufacturing branch of the Bell system.

Operating in the microwave region, this system uses radio frequencies of nearly 5,000,000,000 cycles per second correspond-

ing to a wavelength of less than half the length of an ordinary pencil. The waves can be concentrated into a sharp beam and require a clear unobstructed straight-line path for their transmission. They do not follow the earth's curvature but shoot off into space. Each system can carry eight high-grade telephone channels, any of which can be used for signaling and dialing. If taken out of telephone service, any or all channels will carry telegraph, facsimile, or pictures.

In the demonstration six simultaneous conversations were carried between New York and Neshanic, 40 miles away. At the same time a seventh telephone channel was transmitting the day's weather map by the Army's facsimile system, and over an eighth channel were passing 18 teletypewriter messages, one of which was originated by amateur typists.

Two more pairs of radio sets were then looped in at each end to provide five radio links giving two-way transmission over a total distance of 200 miles. Then, seven channels were themselves looped together to give 1,400 miles of two-way voice transmission by radio. Finally, by changing from two-way to one-way transmission, a 2,800-mile airline circuit was provided with both talker and listener being in New York. This is one of several radio-relay systems now being considered for application by the Bell system.

Pulse Time Modulation of Multiplex Telephone

The first unrestricted demonstration of pulse time modulation of multiplex telephone, telegraph, radiobroadcast, and television transmission was given by the International Telephone and Telegraph Corporation at New York, N. Y., September 27, 1945. The equipment demonstrated can carry 24 or more two-way telephone conversations, or many telegrams, or 12 or more different radiobroadcasting programs at the same time from the same radiobroadcasting center over one radio channel.

Pulse time modulation operates by emitting short pulses of high-frequency radio energy. These pulses are of constant amplitude, and are all of the same carrier frequency. Modulation is effected by transmitting a synchronizing, or "marker" pulse at fixed times, and following this pulse with the "signal" pulse at a variable time interval, the time interval being varied at a rate corresponding to the audio frequency of the signal being broadcast. In the present arrangement a single marker pulse is followed by the 24 signal pulses for the 24 channels.

From the top floor of the 32-story International Telephone Building the pulse time modulation channel goes in a sharp beam to a repeater station near Hazlet, N. J., then to another repeater station at the Federal Telecommunication Laboratories at Nutley, N. J., and from there back to the same room in the International Telephone Building, so that the circuit starts and finishes there, but is in reality an 80-mile long-distance telephone circuit. This long-distance telephone channel carries 24 or more conversations at the same time. Engineers point out that the repeater stations which boost the strength of the circuits' microwave energy are required approximately every 30 miles. These repeater stations operate automatically without any human attendance.

Pulse time modulation which has been referred to previously (*EE, Jan '45, p 43*) was developed by the laboratories division of the Federal Telephone and Radio Corporation.

UET Elects Officers

J. P. H. Perry, vice-president of the Turner Construction Company, New York, N. Y., was elected president of United Engineering Trustees, Inc., at a meeting on October 25, 1945. In this capacity he succeeds F. M. Farmer (A '02, F '13) vice-president and consulting engineer, Electrical Testing Laboratories, Inc., New York, N. Y.

Other officers elected were: R. M. Roosevelt, mining engineer, vice-president; Albert Roberts, secretary-treasurer, Minerals Separation North America Corporation, re-elected treasurer; C. R. Jones (A '16, M '30) eastern transportation manager, transportation division, Westinghouse Electric Corporation, New York, N. Y., re-elected assistant treasurer; John H. R. Arms, secretary of the Engineering Foundation, also re-elected secretary.

The United Engineering Trustees is a corporation which promotes the advancement of the engineering arts and sciences through the Engineering Foundation, and the Engineering Societies Library.

Mica Substitutes Developed to Meet Wartime Shortages

German wartime industry appears to have developed a substitute for mica as an electrical-insulating material that appears likely to remain in the peacetime market as a mica competitor. As disclosed in a report by the Publications Board of the United States Department of Commerce, a resin-impregnated glass fabric known as "Glushartgewebe" was developed by the Robert Bosch Company of Stuttgart for the insulation of commutator segments of its motors, generators, and other such machinery. Governing specifications for the basic glass fabric limited the individual threads to a diameter range of 0.015 to 0.022 millimeter, and a weight of not less than 125 nor more than 135 grams per square meter. The thread counts ranged from 19 to 21 per centimeter in the weave, and from 15 to 17 per centimeter in the warp. A special heat test revealed any excess oil that might have a tendency to remain in the fabric from the sheen process, as such oil would interfere with satisfactory impregnation.

The impregnating solution was a homogeneous mixture of 53.30 per cent (by weight) of partially polymerized resinol, 23.35 per cent alcohol, and 23.35 per cent of osmose-caoline. Machines similar to those used in the United States in the manufacture of varnished cambric were used in the manufacture of the impregnated glass fabric. Adjustable pressure rolls controlled the amount of solution used, at the rate of approximately 42 kilograms of the solution for each 100 meters of fabric. The glass

Nerve Center for Western Wind Tunnel

Westinghouse photo

Master control room of wind tunnel at Pasadena, Calif., where tomorrow's airplanes are being developed, from which all operations are directed and controlled and to which all scientific data are transmitted. This is operated by the California Institute of Technology and owned jointly by Consolidated Vultee Aircraft Corporation, Douglas Aircraft Company, Inc., Lockheed Aircraft Corporation, and North American Aviation, Inc.

fabric entered an oven at room temperature, reached a maximum of 120 degrees centigrade at the top of the oven and cooled to room temperature by the time it left the oven. The travel distance in the oven was about 14 meters.

After impregnation, the fabric was cut into strips 1,500 by 95 mm, folded into three thicknesses lengthwise, and then formed under heat and pressure into a molded piece 500 by 95 mm, the largest possible within the close thickness limits required for commutator insulating strips. Molded under a pressure of 350 kilograms per square centimeters at a temperature of 160 degrees centigrade for a period of five minutes, the material subsequently was given an oven baking at a temperature of 210 degrees centigrade to remove all the solvent.

The physical characteristics of this mica substitute, as reported by the German makers to American investigators, were as follows:

1. Withstood a temperature of 250 degrees centigrade continuously; 320 degrees centigrade for short periods.

2. Nonhygroscopic, showed no change in weight or dimension when exposed to relative humidity of 100 per cent and temperature of 21 degrees centigrade for 24 hours.

3. Withstood a commercial-manufacturing breakdown test of 1,000 volts, but is described as being able to withstand many times that voltage.

No information was indicated concerning the insulation resistance of the material or concerning the effect of humidity on such resistances. Chemists of the Bosch Company have indicated that the substitute material would continue in use even after natural mica again becomes available.

Regulations for Federal Technical Committees

The Federal Specifications Board, composed of representatives from ten Government agencies, has drafted regulations governing the operations of the 74 technical committees under its supervision. The Board was established by C. E. Mack, director of the Treasury's procurement division. In co-operation with the standards branch of the procurement division, it is responsible for the preparation and revision of Federal specifications for supplies used by Federal agencies.

Federal specifications are drafted by the technical committees for promulgation by the director of procurement. Each committee is composed of technical Government personnel and is responsible for drafting specifications on certain commodities.

Serving on these technical committees on a part-time basis are about 1,300 experts from the Government service. According to regulations drafted by the Federal Specifications Board, technical committees are composed of representatives from Government agencies responsible for quality and performance of materials and equipment. Drafts of proposed specifications will be submitted for comment and criticism to Government agencies, representative manufacturers, and recognized technical and professional societies. Among the latter are American Standards Association, American Society for Testing Materials, Society of Automotive Engineers, American Society of Civil Engineers, American Society of Mechanical Engineers, National Institute of Governmental Purchasing, and others. The technical committees will then incorporate any accepted suggestions in the final draft.

Engineers Testify at Senate Hearings on Science Legislation

Appearing in October before the Senate Committee hearings on proposed science legislation (*S* 1285, *S* 1297, and related bills) a panel of five prominent engineers presented engineering viewpoints and recommendations. This panel was appointed by the Engineers Joint Council (formerly known as Joint Conference Committee) and consisted of the following: Boris A. Bakhmeteff, chairman, honorary member, American Society of Civil Engineers; Doctor Harvey S. Mudd, president, American Institute of Mining and Metallurgical Engineers; Professor A. G. Christie, past president, American Society of Mechanical Engineers; F. Malcolm Farmer, Fellow and past president, American Institute of Electrical Engineers; Doctor George Grainger Brown, past president, American Institute of Chemical Engineers.

This panel recommended that:

1. The development of basic scientific research on a scale commensurate with the dominant position of the U.S.A. is a problem of pressing national necessity. The magnitude and urgency of the task make indispensable government support of such research through a National Research Foundation.

2. Federal funds, administered by the Foundation, should be allocated for purposes where government support is indispensable, and should not be diverted to fields where research may rely on other sources. The proposed National Research Foundation should promote basic scientific research only, leaving applications to industrial and technologic practices to the appropriate private, industrial, and public agencies.

3. Basic scientific research should include fundamental research in engineering sciences.

4. Social studies should be the object of a separate agency.

5. The preferable form of organization is to have control of the Foundation vested in a Board appointed solely on the basis of scientific competence and outside of any partisan or political consideration. The Director of the Foundation should be selected by the Board and be responsible to the latter.

6. The Foundation should be given the broadest authority to enact its own rules and regulations in all matters concerning basic scientific research, in subsidizing the training of future research personnel, and in matters of publication.

7. Engineering science should be recognized in the forming of the Board and the divisional substructure.

8. The Legislative Act establishing the Foundation should be confined to the sole purpose of advancing basic science and should not include controversial legislation dealing with patents.

The full text of the official testimony of this panel follows:

ENGINEERS INTERESTED IN RESEARCH

"Engineers are vitally interested in basic scientific research, for such research is the foundation of modern engineering. In fact, the position and role of the engineer in the human community is that of an active link between basic scientific research and technology. It is the engineer who makes use of the fruit of scientific progress and turns it to the practical service of man. Applied research is actually planned and carried out by the engineer. That is his recognized field. However, the engineer is directly concerned with, and actively engaged in, basic scientific research. Indeed, recent progress of technology has grown out of an unprecedented development of engineering science, meaning a fundamental knowledge of the laws of nature which permit the mastery of the resources and powers of nature. The significance of engineering science in present society is best illustrated by the example of Germany, which was the first country to recognize the vital importance of basic engineering research. The result was the miraculous technical achievement of which the world has been the recent witness, and of which humanity came so near becoming a victim.

"In many ways the practicing engineer bears the same relationship to fundamental research in the science of engineering as does the practicing physician to the basic investigations of the scholarly doctor in the medical and biological fields. The practicing engineer applies the basic principles discovered by engineering science to technological problems, just as the practicing physician uses scientific discoveries for healing the sick.

ENGINEERING VIEWPOINT

"In presenting the viewpoint of the engineering profession, which may rightfully consider itself as particularly expert in appraising the value and portent of scientific research, the undersigned panel unreservedly endorses the broad objects of the proposed legislation in regard to basic scientific research. The Engineering Profession stands undivided back of the words of the President, that

'Progress in scientific research and development is an indispensable condition to the future welfare and security of the nation.'

"Furthermore the circumstances under which this country is facing the problem of promoting basic scientific research, are unprecedented and are marked by pressing urgency. By the force of events growing out of the War, the United States has been thrust into a position of pre-eminent leadership in world affairs. It is incumbent on us to continue to preserve and maintain this leading part from this time forward. We must be prepared for any military eventuality. War has become a battle of scientists. Also this country must lead in science to assure national health, prosperity, and welfare. As the President stated:

'No nation can maintain a position of leadership in the world of today, unless it develops to the full its scientific and technological resources.'

"The American people have been foremost in technical ingenuity and industrial organization, and in research of 'applied' character. It is a well-acknowledged fact, on the other hand, that in the realm of basic sci-

ences and basic scientific research the United States did not keep pace with the principal nations of the Old World. Indeed, to a large extent practical applied research in the United States relied on basic scientific material coming from overseas. The war has violently upset this balance. Europe is in eclipse. For years to come, in the intellectual and scientific realm the United States will have to depend on its own resources. This brings this country face to face with a problem of utmost gravity. Under the threat of losing its primacy, the United States 'must' speedily fill the void left open by the ravages of Europe, and within the shortest allowable period bring up its own scientific research to a level which, in scope and quality, will measure up to the requirements of this country's new world position.

"It is self-evident that the size and the urgency of the problem are such that scientific research in this country no longer can be allowed to depend on the course of natural development that prevailed in the past, and to rely upon the diminishing funds of private philanthropy. A systematic and generous yearly appropriation of government funds becomes a necessity. Under such circumstances the Engineering Panel joins its voice to the universally endorsed proposal of a special National Foundation for promoting and developing basic scientific research.

"The situation indeed bears a resemblance to that at the beginning of the war, when the country was called upon to build overnight a war industry capable of meeting the most formidable threat of all time. However, the conversion of our peacetime industry to war was largely a problem of material reorganization, while the present problem of bringing to life and stimulating creative, scientific endeavor largely lies in the spiritual and intellectual realm. Indeed, the delicacy of the problem requires the most careful and considerate approach. Methods must be chosen which would assure an optimum and most speedy development. It is equally imperative to abstain from measures which could impair or stultify the sought-for objective.

RECOMMENDATIONS

"In formulating the following opinions, the undersigned Engineering Panel is motivated by the desire to find the best possible solution for a problem of highest national importance:

(*a*) The primary purpose of the proposed Foundation should be basic scientific research. It is in this realm that the United States has been lagging behind. As a general principle, the Foundation should not spend government funds for research in fields which have been obtaining, and will continue to obtain, financial support from other sources. Accordingly, there is no need for the Foundation to support 'applied, research.' Indeed, experience has shown that adequate funds and means were readily found in the past for research of applied practical character. Also there are many research men and organizations, in the field of technology and applied sciences, that are well supported by industry and partly by special public agencies for the purpose of developing new products and processes for business concerns of all sizes. Federal aid, on the other hand, is sorely needed and should be generously provided to enhance and support basic scientific research. The latter obviously is the foundation for practical applied advancement. But basic research in itself bears the distinction of being undertaken without any immediate idea of profit. The results are to be of service to humanity at large.

(*b*) It is the view of this panel that basic scientific research necessarily implies fundamental research in the engineering sciences. Although none of the proposed legislative proposals has so far deigned to mention engineering research by name, we feel that it is unnecessary as well as impractical to enumerate the different ramifications of science in the proposed Legislative Act. Research in the sciences should mean that the Foundation will promote basic scientific work on all possible lines, recognizing fundamental engineering research as one of its major objectives.

(*c*) In the opinion of this panel no useful purpose will be served by extending the scope of the Foundation to embrace 'social sciences.' The engineers in their wide contacts with 'men' keenly appreciate the value and significance of better social understanding. The character of the problems, however, is essentially distinct from those dealing with the physical world. Social studies should be the object of a separate agency composed of an altogether different type of man. Placing social sciences under the same roof with natural sciences will help neither and impede both.

(*d*) In discerning the ways and means by which optimum progress in basic scientific research can be achieved, the undersigned panel wholeheartedly ranges itself back of the words of the President, that:

'Science can be co-ordinated and encouraged, it cannot be dictated to or regimented. Science cannot progress unless it relies on the free intelligence of the Scientist . . . the Federal Research Agency . . . should in no way impede that freedom.'

In deciding upon the preferred form of organization and on the modes of functioning of the Foundation, this panel is guided by the conviction that progress in science is essentially a matter of free and uninhibited display of creative scientific endeavor. Accordingly, any plan intended to call to life and promote basic scientific research must devolve from the aim of providing a propitious atmosphere, in which creative human talent will assert itself to supreme advantage. Reduced to practice, the problem is to select scientists endowed with creative capacity and to place them in an environment where, with proper material support, scientific talent will thrive and bear fruit.

With regard to the form of organization, the essential feature is to place the Foundation in the hands of men, competent and experienced in scientific research and removed from all possible partisan or commercial influences. The type of organization, proved by the example of the large universities, the National Advisory Board for Aeronautics, and the numerous privately endowed non-profit institutions, is the American democratic method of group control as distinct from centralized authority exercised by a single official. The undersigned panel decidedly expresses its preference, therefore, for the type of structure reflected in the Magnuson Bill *S* 1285, which vests supreme control of the Foundation's affairs in a board, the members of which are chosen without regard to political or partisan affiliations and solely on the basis of their demonstrated interest, experience, and competence in matters of research.

Research, by its very nature, requires a 'climate' different from the technical formalities attendant on customary government routine. The Foundation should be given the widest authority to prescribe its own specific rules and regulations and to administer affairs in forms appropriate to the purpose of advancing basic sciences, and outside the usual bureaucratic routine.

(*e*) A Foundation of the size and scope contemplated will obviously require a strong and efficient executive structure. Accordingly, the Director should possess the broadest powers to insure promptness and efficiency in operations. But in his capacity as Chief Executive the Director should function under the general control of the board and should be responsible to the latter.

The board should consist of men, representing different ramifications of science and should be selected from panels submitted by the leading national scientific and professional associations. The board should necessarily include members representative of engineering. Engineering scientists should also be appointed to the different committees, which are to govern the work of the divisional sub-structure. The board should be left free to seek recommendations for committee appointments from appropriate scientific and professional associations. No single body should be privileged by legislative acts to offer such recommendations.

(*f*) The most crucial problem is that of men. There is need for scholars capable of creative leadership and for adequate staffs of scientifically trained personnel. The supply of such personnel has been diminishing in recent years and shows no prospect of immediate renewal. There is no way to provide for such personnel in the future except by generously appointing promising candidates to fellowships and scholarships. The training of such future scientific personnel must be raised to the highest possible level, commensurate with the requirements of the day. To achieve this purpose, and to procure in the shortest time an adequate host of properly trained men, may require policies and procedures in the way of fellowships and stipends which might substantially depart from previous practices and would boldly cut across routine. The Foundation should be given the broadest possible freedom of action in this respect.

The natural seat for the training of personnel is the universities. Except for a few privately endowed non-profit institutions and certain Government laboratories, the universities will also be the natural center for basic scientific research. By contrast to the Old World prototypes, where for centuries the universities flowered as centers of creative scientific activity, the American university in the past principally served the purpose of mass instruction. The duties connected with teaching left no time and opportunity to the academic personnel for scientific research and advancement. Under the stress of the new national requirements the climate of university life will necessarily have to change. The Foundation in its policy of contracts and subventions should be free to exercise such powers as will allow University Research to be located in surroundings where the scientifically minded staff will be able to devote the necessary time and effort to scientific pursuits free from the consuming burden of academic routine.

(*g*) In laying emphasis on basic scientific research as the prime objective of the proposed Foundation, this panel fully recognizes the fact that it is not always possible to draw the delimiting line between basic and applied pursuits. It is obvious, on the other hand, that all such activities as experimental researches looking to the development of new or the improvement of existing processes and devices, or the preparation of plans, specifications, standards, economic and industrial studies, or the experimental operation of pilot plants should not be included in the function of the Foundation. These most necessary and useful activities are the proper function of private industry, industrial research laboratories, engineering organizations, and the appropriate federal, state, or municipal agencies. A National Research Foundation should not only refrain from duplicating such activities, but should not utilize its facilities or energies for the immediate commercial advantage of any group of citizens. On the other hand, the work of the Foundation will ultimately aid all practical endeavor by extending the limits of basic knowledge and by increasing the supply of men trained for research.

(*h*) An essential condition to the success of a Foundation dedicated to the advancement of basic sciences, is to divest such Foundation from all duties and functions which are essentially alien to the spirit of free scientific pursuit. A most important instance of this character is the question of patents. The subject of patents is highly controversial. Patents have been qualified by some as 'the life of research.' Others are inclined to consider the very idea of patent protection as 'an embodiment of monopoly.' This panel understands that the whole subject of future national patent policies is in the process of consideration by special legislative agencies. In view of this fact and pending the forthcoming patent legislation, a Foundation dedicated to basic scientific research should be held free from any connections with predetermined patent policies. Moreover, patents have to do primarily with applied or industrial research, as distinct from the basic scientific research with which the Foundation should be concerned. If the Foundation is properly set up for the object of advancing basic sciences, the question of patents will not be serious, and in rare, exceptional instances, could be properly handled under the provisions of the general patent law through appropriate contractual relationships determined by the Board."

New System Requires One Frequency for Sound and Vision

A new system of television transmission embodying the transmission of sound by pulses similar to the small bursts of radio waves lasting but a few millionths of a second used in radar was announced October 31, 1945, by Pye, Ltd., a British firm. This system effects a televised program with sound by a single transmitting unit. Hitherto, a transmitting station had to have two single-purpose transmitting units, one to transmit the picture, and the other to broadcast sound. The public had to have a vision receiver and a sound receiver, either on separate sets or housed in one cabinet.

Use of the new system is said to reduce considerably the cost of television both for the broadcasting station and for home users. Again, the transmitting station will be able to reduce the equipment, as well as to cut down running costs. For the public the elimination of the sound receiver would mean a valuable saving on tubes and other components. When the television transmitter

is in operation, there are short intervals of time during which no signal is being broadcast. These intervals occur during the time that the spot which traces the picture is returning to its starting point preparatory to making another line, and each represents approximately one-tenth of the total transmission time. Each of these idle periods lasts for ten-millionths of a second, and there are 10,000 of them during each second. It would now be possible to use the television transmitter during these idle periods to transmit the sound program. This would be done by taking a "sound snapshot" of the sound part of the program whenever the transmitter is not transmitting the vision part of the program. Using television of the present definition, 10,125 of these "sound snapshots" are transmitted per second.

The process is best compared with that of taking motion pictures. Thus, if the sound snapshots passed into a suitable receiver at the rate of 10,125 per second, the original sound program could be recovered. The sound snapshot is really a pulse similar to a radar pulse which is sent out by the picture transmitter, and the width of which is made to vary according to the sound that has been transmitted. With the system in operation, this modification to the transmitted wave form would enable both vision and sound to be transmitted on a single carrier by a single transmitter with a single aerial system. This pulse would be separated from the picture program in the television receiver and the variation of its width would be made to operate a loudspeaker.

The new system embodies other far-reaching improvements such as, eliminating interference in the television receiver between sound and vision.

Products Exposition in Chicago

The first of the "Products of Tomorrow Exposition," an industrial fair that will be presented annually in Chicago, Ill., will be held beginning April 27, 1946, and tentative plans call for a 24-day run. A nonprofit organization composed of American business men is behind the project. An announcement has been made that the exposition is being designed as a springboard for world industry to assist in the introduction of new designs, new inventions, and other developments to the general purchasing public as well as to the trade world as a whole. It will not be confined to any one phase of the industrial world or any one country and will be international in scope. Already England, Switzerland, Sweden, and Holland have made inquiries revealing interest in similar exhibits in those countries. Canada and South America are also interested in such expositions.

Both consumer and industrial products will be featured at the Chicago exposition, where a novel one-way traffic plan will ensure guidance to every exhibit and expedite the thousands of visitors expected. A nominal charge for admission will be in effect. No restrictions will be placed on the design of the displays although they will have to conform to the over-all picture of modern interior design.

The planning will be under the direction of Marcus Hinson, electronics engineer and physicist.

New Television Tube Assures 24-Hour Coverage

A new television camera tube more than 100 times as sensitive as any previously used in the studios which picked up scenes with infrared rays in a blacked-out room was demonstrated in a studio of the National Broadcasting Company, New York, N. Y., October 25, 1945. Evidence of the superiority of this new electronic "eye"—a wartime secret—known as RCA "Image Orthicon" came in the transmission of scenes from a rodeo being held in an indoor arena which showed its advantages over the conventional television pickup tubes in providing greater depth of perception and clearer views under shifting light conditions.

The tube was designed and developed by engineers of the Radio Corporation of America at Princeton and Camden, N. J. Credit for its creation was given largely to Doctors Albert Rise, Paul Weiner, and Harold Law of the laboratory staff and to V. K. Zworykin (M '22) associate director.

Especially suited for remote use out of doors under conditions of lighting "that would make the use of ordinary means impossible," the tube is 15 inches long, 3 inches in diameter, of light weight and is easy to use and operate according to the engineers. Its "seeing ability" is one-tenth that of the human eye and is about as sensitive as ordinary high-speed film.

Engineers listed specific advantages in performance of the new device. They are:

1. It extends the range of operations to practically all scenes of visual interest particularly those under low-lighting conditions.

2. Its improved sensitivity, permits greater depth of field and inclusion of background that might otherwise be blurred.

3. Its improved stability protects images from interferences due to exploding photo flashlight bulbs and other sudden bursts of brilliant light.

4. Its smaller size facilitates use of telephoto lens.

Figure 1. Television-camera "eye" known as the "Image Orthicon"

5. Its light weight is useful for portable television cameras.

6. Improved control provides unvarying transmission, despite wide fluctuations of light and shadow.

E. W. Engstrom, research director of the corporation's laboratories, explained that early models were built before World War II in an effort to improve the quality of television transmission. When war came the Armed Forces found need for television applications, and research and development continued at an accelerated pace in response to military requirements. The Image Orthicon tube emerged in its present form much sooner than would normally have been possible. No longer a military secret the tube makes use of 20 years of research not only in television pick-up tubes but also in electron optics, photo-emission, processes, electron multipliers, and special materials. According to Mr. Engstrom "we are today mere amateurs in its ultimate application."

J. F. Royal, vice-president in charge of television, National Broadcasting Company, declared that . . . "assures television of 24-hour coverage, in daylight, twilight, or moonlight—in good weather and in bad."

Figure 2. Scenes from the recent rodeo at Madison Square Garden, New York, N. Y. are picked up by the new television camera (foreground) and by a conventional camera

HONORS

J. M. R. Fairbairn to Receive Sir John Kennedy Medal

The Sir John Kennedy Medal for 1945 will be given to J. M. R. Fairbairn, retired chief engineer of the Canadian Pacific Railway. A graduate in civil engineering from the University of Toronto in 1893, Doctor Fairbairn's career with the Canadian Pacific Railway began in 1901 when he became principal assistant to the district engineer at Montreal, Quebec. His promotions were rapid until in 1918 he was appointed chief engineer of the system, a position which he filled continuously for more than 20 years until his retirement January 1, 1939. In 1941 Doctor Fairbairn accepted the position of director of works and buildings in the naval service of the department of national defense at Ottawa, Ontario, from which he resigned in 1942.

The medal, which is awarded as a recognition of outstanding merit in the profession, commemorates the great services rendered to the development of Canada, to engineering science, and to the profession by the late Sir John Kennedy, past president of the Engineering Institute of Canada.

OTHER SOCIETIES

Material Handling Society Formed

A new society known as the Material Handling Society was formed in Pittsburgh, Pa., October 8, 1945. The suggested objectives are as follows:

1. To further the application of good material handling practices.
2. To encourage an interchange of ideas among the members.
3. To promote education and training in the science and practice of practical co-ordinated material handling.
4. To arrange for the collection and dissemination of information relating to all phases of material handling.

Temporary officers elected were: T. O. English, Aluminum Company of America, chairman, and Richard Rimbach, Materials Publishing Company, secretary. Several committees were organized, such as the program, membership, and nominating committees.

Further information may be obtained from Richard Rimbach, 1117 Wolfendale Street, Pittsburgh 12, Pa.

Canadian Group Aids Community Planning. Assistance in creating a national organization to foster community planning has been offered by the Engineering Institute of Canada, Montreal, Quebec, Canada, in a letter to all provincial representatives at the Dominion-Provincial Conference on Reconstruction. The institute believes that some such organization can be developed into an instrument of great significance and usefulness. This support from the institute is in line with the resolution passed at the annual meeting of the institute at Winnipeg, Canada, wherein such an organization was proposed.

Future Meetings of Other Societies

American Association for the Advancement of Science. March 27–29, 1946, St. Louis, Mo.

American Society for Testing Materials. Forty-ninth annual meeting. June 24–28, 1946, Buffalo, N. Y.

American Society of Heating and Ventilating Engineers. 52d annual meeting, January 28–30, 1946, New York, N. Y.

Illuminating Engineering Society. National convention, September 18–21, 1946, Quebec, Quebec, Canada.

Institute of Aeronautical Sciences. Wright Brothers Lecture. December 17, 1945, Washington, D. C.; 14th annual meeting. January 1946, New York, N. Y.

Institute of Radio Engineers. Winter technical meeting. January 23–26, 1946, New York, N. Y.

Louisiana Engineering Society. Annual Meeting. January 10–12, 1946. New Orleans, La.

National Association of Corrosion Engineers. Annual meeting and convention. May 7–9, 1946, Kansas City, Mo.

EDUCATION

Hoboken Cities Exchange Greetings. In commemoration of the 75th anniversary of the founding of Stevens Institute of Technology, Hoboken, N. J., the mayor of Hoboken, Antwerp, Belgium, has sent greetings to Hoboken, its sister city, in the United States. The mayor's letter, which congratulated the institute for its accomplishments during three quarters of a century, was prompted by greetings sent to him from Stevens Institute of Technology via the Belgian Information Center in May 1945.

More Eastman Kodak Fellowships. The establishment of three fellowships has been announced by the Tennessee Eastman Corporation, Kingsport, a subsidiary of the Eastman Kodak Company, Rochester, N. Y. These include one postgraduate-doctorate fellowship in textile chemistry, and two postgraduate master-degree fellowships—one in textile engineering, and one in textile chemistry. The latter two fellowships will be awarded to different institutions each year. The fellowships granted by the parent company were referred to previously (*EE, Oct '45, p 377*).

Professional Teamwork at Stevens. While problems of national economy and education confront the country, the severest tests will come "in the every-day experiences of human relationships, of personal contacts," according to J. B. Blandford, Jr., administrator, National Housing Agency, speaking at the recent commencement exercises of Stevens Institute of Technology, Hoboken, N. J. Mr. Blandford asserted that even more important than technology, resources, or science, are the factors of collective bargaining, international relations, co-operation between professions, teamwork between Congress and the administrative branch of Government, and the relations between Government, individuals, and private enterprise—especially in attitudes between a citizen and his government.

Mathematics for Servicemen. The services of a mathematical consultant and a noncredit refresher course in high-school algebra and geometry are included in a program adopted by the mathematics department, University of Illinois, Urbana. Funds for the program, which is to aid veterans to adjust themselves to the study of mathematics, are provided by the university's division of special service for former Servicemen.

Housing for Veterans at Michigan. To relieve the housing shortage created by the admission of married veterans, the University of Michigan, Ann Arbor, has leased 39 side-by-side two-family portable dwellings from the abandoned Willow Run housing project at the Willow Run Bomber Plant outside Ann Arbor. The units, which will be transported to a site on the edge of the campus, will accommodate 78 veterans' families, will cost $25 per month, and will be completely furnished.

Homes for Married Veterans at Yale. A bureau to handle the housing problems of married discharged Servicemen who have resumed their education at Yale University, New Haven, Conn., has been established. Property owners and real estate agents cooperate by supplying information about vacancies and suitable accommodations. Several houses owned by the university, which before the war were used as dormitories for unmarried students and during the war were occupied by soldiers attached to the Army training school units at the University, will be made available.

Gift to Charlottesville for Peace. A fund of $300,000 has been given by J. H. Jones, former United States secretary of commerce, to create a Woodrow Wilson school of international affairs at the University of Virginia, Charlottesville. The campus where public affairs and world peace will be discussed was recently the site for training United States officers for military government in foreign lands.

Guidance for Veterans at Stevens. A Veterans Administration Guidance Center has been established at Stevens Institute of Technology, Hoboken, N. J. The center will be equipped to serve 150 veterans per week including men and women. Its purpose is to give advice or consultation along either vocational or educational lines to veterans eligible for such service under the "G.I. Bill of Rights."

New Library for Princeton Students. A construction contract has been let for the Harvey S. Firestone Memorial Library at Princeton University, Princeton, N. J. At present Princeton University has 1,000,000 volumes. About 800,000 will be placed in the new library which will accommodate more than 1,700,000 volumes.

INDUSTRY

Training Opportunities for Veterans. A procedure for approving institutions in New York State offering on-the-job training to veterans under the "G.I. Bill of Rights" has been put into operation. The system, worked out by the State Labor Department and division of veterans' affairs, is aimed at guaranteeing to the veteran training which will equip him to earn a decent living in the field of his choice. All institutions and firms offering training programs are thoroughly investigated before approval. An advisory group composed of representatives of management, workers, and veterans works closely with the assistant commissioners in passing upon the merits of each proposed program. Industrial Commissioner Edward Corsi has announced that training opportunities for as many as 400 veterans have been approved and made available in a single day's operations.

Wilmington Company to Develop Plastics. Plans for a new plastics laboratory at its Parlin, N. J., plant has been announced by the Hercules Powder Company, Wilmington, Del. The laboratory will serve as headquarters for development and research on plastics, and tests will be conducted there on three plastics—ethyl cellulose, cellulose acetate, and nitrocellulose. New mixing equipment used in making plastics for experimentation and a new drawing press for laminating plastics are included in the laboratory project. Construction will start early in 1946.

Lighting Exposition Planned. The first international lighting exposition and conference will be opened in Chicago, Ill., April 25, 1946. It is being sponsored by the National Electrical Manufacturers Association, New York, N. Y. Consulting engineers, architects, building managers, electrical contractors, and executives of industrial and commercial establishments will have an opportunity to obtain first-hand information about the better and more efficient lighting units for industrial plants and offices. As a part of the exposition a series of lighting conferences will be conducted at which recognized authorities will discuss the latest trends in lighting practice.

"Forticel" New Plastic Announced. Development of a new plastic, "Forticel," was recently announced by Celanese Plastics Corporation, a division of Celanese Corporation of America, New York, N. Y. Made from cellulose and propionic acid it was a laboratory plastic for years until the Celanese company succeeded in developing a new process for producing propionic acid from natural gases in commercial quantities and at reasonable prices. Forticel is the result of years of intensive research devoted to the study of scores of chemical combinations developed by introducing organic acid or alcohol radicals into the cellulose molecular chain. As a thermoplastic, the most economical process for making Forticel into finished articles is by injection and extrusion molding according to the company. The new plastic has a low specific gravity, and has excellent electrical properties. Because of low-moisture absorption, its electrical properties are said to be little affected by changes in atmospheric conditions. It is believed that the properties of this plastic will enlarge the field of applications of the widely used cellulosic plastics.

Notebook for Engineers. The *Neoprene Notebook*, a quarterly "sourcebook for engineers and designers" containing facts about Neoprene, has resumed publication as of September 1945. Established in 1938, it was issued regularly until the summer of 1942. It is published at Wilmington, Del., by the rubber chemicals division of the E. I. du pont de Nemours and Company, Inc.

Edison Centennial Committee Formed. Formation of the Thomas A. Edison Centennial Committee which will conduct the international observance of the 100th anniversary of the birth of Thomas A. Edison on February 11, 1947, has been announced. C. F. Kettering (A '04, F '14) president of the American Association for the Advancement of Science, and vice-president in charge of research, General Motors Corporation, Dayton, Ohio, will be chairman of the committee.

Westinghouse Laboratory Opens in West. A new laboratory to which western industry can bring for study its problems of peacetime production by making use of scientific methods of high-frequency heating was opened recently by the Westinghouse Electric Corporation in Los Angeles, Calif. Doctor Russell A. Nielsen (M '45), formerly of the company's research laboratories at East Pittsburgh, Pa., will be in charge of the new laboratory.

Chemical Industries Exhibit. The 20th Exposition of Chemical Industries will be held in Grand Central Palace, New York, N. Y., February 25 to March 2, 1946. The announcement stated that the exposition, coming at a time when industries are in the throes of reconversion, will serve as an accelerator, providing opportunities for personal contact and business conferences among principals, technical staffs, manufacturers, and professional consultants.

Bell System to Construct Electronic Plant. As a part of the Bell Telephone System's postwar construction program, Western Electric Company has purchased property and will construct a new electronic-components plant at Allentown, Pa. In the new plant the company plans to manufacture vacuum tubes, quartz crystals, temperature-sensitive devices, and other precision products for use in the System's communications facilities and in other commercial applications.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Voltage and Current Relations for Controlled Rectification With Inductive and Generative Loads

To the Editor:

In his interesting investigation about certain rectifier problems[1] K. P. Puchlowski remarks very correctly that analytical methods to deal with some rather basic rectifier relations are insufficiently treated in technical literature. I found that a simple analytical solution of some rectifier problems is available, if as an approximation the sine wave $y = A \cos \omega t$ is substituted by a parabola

$$y = A\left(1 - \frac{\omega^2 t^2}{2}\right)$$

This approximation gives very accurate results for a rectifier working period near the peak of the sine wave. I published this method to attack some rectifier problems in connection with calculations of half-wave battery charger in *Electrical Engineer and Marchandiser* (Melbourne, Australia), July 15, 1944. A similar substitution of a sine wave

$y = A \sin \omega t$

near its change of polarity would be

$$y = A\left(\omega t - \frac{\omega^3 t^3}{6}\right)$$

BENNO GERSTMANN (A '41)

(Electrical engineer, Australian Block and Chain Company, Melbourne)

REFERENCE

1. Voltage and Current Relations for Controlled Rectification With Inductive and Generative Loads, **K. P. Puchlowski.** AIEE *Transactions*, volume 64, 1945, May section, pages 255–60.

Nomogram for Frequency Formula

To the Editor:

The familiar equation

$$f = \frac{1}{2\pi\sqrt{LC}}, \text{ in which}$$

L = inductance in henries
C = capacitance in farads
f = frequency in cycles per second

is awkward to compute, but it lends itself to the three-parallel-line nomogram of the utmost simplicity and usefulness, and this is solved by a single secant cutting the three scales. To visualize it, assume three central sliders from any ten-inch slide rule. Place these upright near each outer edge of a paper, with the bottoms having unit graduation against a horizontal base line so that the graduations read upward. These will be the L and C scales. Place the third midway between the two, but upside down, so that the graduations increase downward and so aligned vertically that the base line intersects it at the graduation $\frac{1}{2\pi} = 0.159$. This will be the f scale and will require an extension. Use the same modulus (length from one to ten) for all three scales. Then, any straight line (computing secant) across all three, cuts out values that satisfy the equation. For $L = 1$, $C = 1$, $f = 0.159$ as computed from the equation.

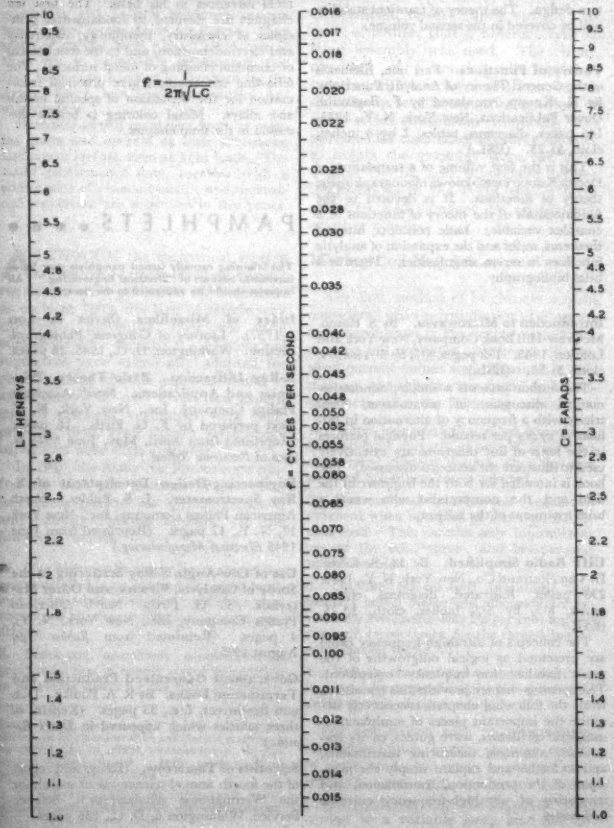
Actually, the graduations may be ticked off from the ten-inch modulus of the slider.

To increase its range the following rules are quite evident:

If *either* L or C is divided by 10^2, 10^4, and so forth, then f will be multiplied by 10, 10^3, . . .
If *either* L or C is multiplied by 10^2, 10^4, and so forth, then f will be divided by 10, 10^3, . . .

If *both* L and C are divided by 10, 10^3, 10^5, and so forth, then f will be multiplied by 10, 10^2, 10^3, . . .

If *both* L and C are multiplied by 10, 10^3, 10^5, and so forth, then f will be divided by 10, 10^2, 10^3, . . .



If inductance is in millihenries and capacitance in microfarads, the practical units, the inductance scale is to be multiplied by 10^3 and the capacitance scale by 10^3.

CARL P. NACHOD (A '07)

(Vice-president, Nachod and United States Signal Company, Inc., Louisville, Ky.)

NEW BOOKS

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Controllers for Electric Motors. By H. D. James and L. E. Markle. McGraw-Hill Book Company, New York, N. Y., 1945. 324 pages, illustrated, diagrams, charts, tables, 9 by 5¾ inches, cloth, $3.50. (ESL.)

The construction, performance, and operation of all types of commercial motor controls in general use are described. Protective devices are explained in detail, and brief instructions for installation and maintenance are included. Special control systems, such as for elevators, steel mills, and so forth, are not considered. The book is intended for technical students as well as for operating men and application engineers, and the treatment is such that only a limited knowledge of electric motors is required.

Electrical Power Uses in Marine Service. (Marine Electricians' Library, volume 3.) By J. M. Dodds. McGraw-Hill Book Company, New York, N. Y., and London, England, 1945. 444 pages, illustrated, diagrams, charts, tables, 8½ by 5¼ inches, cloth, $4. (ESL.)

This volume presents the fundamentals of the ordinary incandescent lamp, as well as new applications of electrical principles in modern lamp sources. It also discusses the various new lamps for shore-plant and marine use, such as mercury-vapor lamps, marine searchlights, and the fluorescent lamp in illumination. The electrical propulsion of ships is discussed under two divisions: direct current for the relatively small power plant, and alternating current for the larger ship-propulsion plant.

Electromagnetic Engineering. Volume 1, Fundamentals. By R. W. P. King. McGraw-Hill Book Company, New York, N. Y., 1945. 580 pages, diagrams, charts, tables, 8½ by 5¼ inches, cloth, $6. (ESL.)

This first volume of a three-volume series offers a systematic introduction to basic concepts of electromagnetism which are fundamental in the study of electromagnetic waves, antennas, electromagnetic horns, wave guides ultrahigh frequency, and microwave circuits. The physical and mathematical essentials of electrodynamics are developed logically and discussed critically for the purpose of application to engineering problems.

Procedure Handbook of Arc Welding Design and Practice. Eighth Edition. The Lincoln Electric Company, Cleveland 1, Ohio, 1945. 1,312 pages, illustrated, 6 by 9 inches, simulated leather, $1.50 in United States, $2.00 elsewhere.

Includes details of the most recent welding methods and techniques. Many new illustrations cover significant welding applications developed in various phases of war production. In addition to standard data on welding symbols, speeds and costs, characteristics of metals, preheating, and stress relieving, the revised handbook includes 16 new subjects, such as underwater cutting, shop ventilation, methods of testing, mathematical calculations for new weld-designed structures, and filler-metal specifications for arc-welding electrodes.

Elementary Electric-Circuit Theory. By R. H. Frazier. McGraw-Hill Book Company, New York, N. Y., 1945. 434 pages, 8¼ by 5¾ inches, cloth, $4.

Designed as a complete elementary exposition of electric-circuit theory requisite in the technical foundation of all students of electrical engineering regardless of their expected branches of specialization—electric power, communications, or electronics. A knowledge of physics that usually is acquired by the end of the sophomore year is adequate. Provides a basis for the more advanced study of power-system networks, communications networks, electron-tube circuits, and associated apparatus. By the use of problems a broad view of the frequency spectrum is given. The book is amply provided with references to historical sources, that show the origin of the various laws, principles, and theorems that are presented.

Thomas' Register of American Manufacturers. 35th edition, 1945. Thomas Publishing Company, New York, N. Y. No pagination, illustrated, 14¾ by 9 inches, cloth, $15. (ESL.)

This directory, over 6,000 pages in size, is a guide to the manufacturers and importers of practically every commercial product. The products are listed alphabetically in the main list, with the names and addresses of manufacturers and their capital ratings. An alphabetical list of manufacturers shows their branch offices. An extensive list of brand names enables manufacturers of brand goods to be found.

Piping Handbook. 4th edition. By S. Crocker. McGraw-Hill Book Company, New York, N. Y., and London, England, 1945. 1,376 pages, illustrated 7¼ by 4½ inches, cloth, $7.00. (ESL.)

This standard work makes available under one cover a compilation of data for the effective design and use of piping in all its engineering and industrial applications. The book authoritatively covers scientific fundamentals, materials, design and installation practice, and many useful construction details. Separate chapters are devoted to closely allied topics, such as pumps and corrosion.

Plastics in Practice, a Handbook of Product Applications. By J. Sasso and M. A. Brown, Jr. McGraw-Hill Book Company, New York, N. Y., and London, England, 1945. 185 pages, illustrated, diagrams, charts, tables, 11 by 7½ inches, cloth, $4. (ESL.)

This book brings within one cover a practical review of plastics in all their successful commercial applications, providing a handy key to the essential facts on how and why plastics are used. The treatment is organized around 103 actual uses of plastics, reviewing the problems encountered in developing them and outlining the reasons for the solutions adopted.

Power-System Stability, Volume 1, Steady-State Stability. By S. B. Crary. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1945. 291 pages, illustrated, diagrams, charts, tables, 8¾ by 5¼ inches, cloth, $4. (ESL.)

The fundamental theory underlying maintenance of continuous electric power under normal and abnormal operating conditions is to be provided by a two-volume set of which this is the first. The present volume devotes the first five chapters to the theory required for a study of the steady-state-stability characteristics of a system; the last seven chapters discuss the applications of the theory to system design. The theory of transient stability will be covered in the second volume.

Theory of Functions. Part one, Elements of the General Theory of Analytic Functions. By K. Knopp, translated by F. Bagemihl. Dover Publications, New York, N. Y., 1945. 146 pages, diagrams, tables, 7 by 4 inches, cloth, $1.25. (ESL.)

This is the first volume of a translation of Doctor Knopp's well-known monograph on the theory of functions. It is devoted to the fundamentals of the theory of functions of a complex variable: basic concepts, integral theorems, series and the expansion of analytic functions in series, singularities. There is a brief bibliography.

Introduction to Microwaves. By S. Ramo. McGraw-Hill Book Company, New York and London, 1945. 138 pages, 8½ by 5¼ inches, cloth, $1.75. (ESL.)

The author presents a simple, nonmathematical discussion of microwaves, electricity with a frequency of alternation in billions of cycles per second. Physical pictures in the form of line diagrams are extensively used to illustrate the concepts discussed. The book is intended for both the beginner in the field and the nonspecialist who wants a brief treatment of the subject.

UHF Radio Simplified. By M. S. Kiver. D. Van Nostrand Co., New York, N. Y., 1945. 238 pages, illustrated, diagrams, chart, tables, 8½ by 5½ inches, cloth, $3.25. (ESL.)

The concepts of ultrahigh-frequency radio are presented as logical outgrowths of the more familiar low-frequency equipment. The opening chapter provides this transition, while the following chapters successively describe the important pieces of equipment—magnetic oscillators, wave guides, cavity resonators, antennas, measuring instruments, and so forth—and explain simply the principles of the production, transmission, and measuring of ultrahigh-frequency currents and waves.

Electronics Dictionary. By N. M. Cooke and John Markus. McGraw-Hill Book Company, Inc., New York, N. Y., 1945. 433 pages, illustrated, 5½ by 8¼ inches, $5.

This is an up-to-date glossary containing definitions of more than 6,000 terms used in radio, television, industrial electronics, communications, facsimile, and sound recording. The book is written primarily at the level of the student, but the language of electronics is explained also for the engineers who must develop applications for electronic equipment and for those who must use and maintain such equipment. The authors have tried to set up a complete and consistent policy for abbreviating electronic terms based upon the groundwork laid by American Standards Association.

Electroplating, a Survey of Modern Practice, including the Analysis of Solutions. By S. Field and A. D. Weill. 5th edition. Pitman Publishing Corporation, New York, N. Y., and Chicago, Ill., 1945. 483 pages, illustrated, 7 by 5 inches, cloth, $5. (ESL.)

The object of this book is to provide the practical plater with a review of the technical advances in his field. The first ten chapters are devoted to fundamental principles of chemistry, metallurgy, electricity and electrodeposition, and to the mechanical or chemical cleaning of metal surfaces. The following ten chapters give practical information for the deposition of specific metals and alloys. Metal coloring is briefly discussed in the final chapter.

PAMPHLETS • • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquries should be addressed to the issuers.

Index of Microfilms (Series A—Lots 1–1737). Library of Congress, Photograph Section. Washington, D. C., 1945, 26 pages.

X-Ray Diffraction. Basic Theory, Principles and Applications. North American Philips Company, Inc., New York, N. Y. Text prepared by F. G. Firth. 16 pages. (Reprinted from April, May, June 1945 issues of *Petroleum Refiner.*)

Engineering-Design Development of X-Ray Spectrometer. J. S. Buhler. North American Philips Company, Inc., New York 17, N. Y., 12 pages. (Reprinted from June 1945 *Electrical Manufacturing.*)

Use of Low-Angle X-Ray Scattering in the Study of Catalysts, Viruses, and Other Materials. F. G. Firth. North American Philips Company, Inc., New York, N. Y., 4 pages. (Reprinted from *Rubber Age,* August 1945).

Government Guaranteed Production and Termination Loans. By R. A. Foulke. Dun and Bradstreet, Inc., 35 pages. (Reprint of three articles which appeared in *Dun's Review.*)

Scientists of Tomorrow. (Essays and report of the fourth annual science-talent search for the Westinghouse scholarships.) Science Service, Washington 6, D. C., 136 pages.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Resonant-Circuit Constant-Current Regulators

G. M. KEVERN
ASSOCIATE AIEE

Synopsis: Airport-approach and runway-marker light circuits are quite similar to the usual street-lighting circuits, except that the important additional feature of brightness control is required. Standard moving-coil regulators were found to be unsatisfactory for this purpose, and so the development of resonant-circuit constant-current regulators with built-in brightness control was fostered by the Army Air Forces. Four years of service have proved regulators of this type to be entirely satisfactory, and they have been adopted as standard by the Army, Navy, and Civil Aeronautics Administration.

Resonant-circuit regulators have no moving parts and operate at high efficiencies and power factors, even at light loads. Detailed performance data, together with a comparison of resonant-circuit and moving-coil regulators, are presented in this paper.

ALTHOUGH the theoretical aspects of resonant-circuit constant-current regulators were published by Steinmetz as early as 1900, the lack of satisfactory capacitors prevented their use until comparatively recently.[1] Moving-coil regulators were universally adopted for street-lighting circuits and were found so satisfactory that only a very few experimental resonant regulators were built prior to 1940, even though satisfactory capacitors were then available.

In 1940, the Army Air Forces were confronted with the problem of providing brightness control for airport-approach and runway lighting circuits, for the following reasons:

1. The high-candle-power lamp assemblies being installed in an attempt to permit landings under adverse weather conditions were sometimes blinding under clear weather conditions.

2. Black-out operations necessitated a great reduction in candle power in addition to providing hoods for the lamp assemblies.

Paper 45-165, recommended by the AIEE committees on air transportation and electric machinery for publication in AIEE TRANSACTIONS. Manuscript submitted August 1, 1945; made available for printing August 17, 1945.

G. M. KEVERN is chief of the lighting unit, equipment laboratory, Air Technical Service Command, Wright Field, Dayton, Ohio.

The brightnesses found to be necessary, together with the average currents which most nearly produce those brightnesses on all the lamp assemblies used, are as enumerated in Table I.

Runway and approach lighting circuits in use in 1940 were nearly identical with conventional street-lighting circuits, except, of course, that a different type of lamp assembly was used. The circuit consisted of a moving-coil regulator, together with a series circuit from two to six miles in length. A series–multiple or series–series transformer frequently was provided for each lamp assembly in order to isolate the assembly from the high-voltage circuit and to prevent service interruptions in the event that a lamp assembly was damaged by an airplane or other vehicle.

Moving-Coil Regulators

The first method of brightness control considered was the installation of a tapped autotransformer in the output circuit of a moving-coil regulator. Although the desired current values were obtained in this manner, the scheme was found to be unsatisfactory for the following reasons:

1. When connected to a rated lamp load, the regulator operates at only 20.5 per cent of its rated kilowatt output, when the one-per-cent brightness tap is selected.

2. Conventional moving-coil regulators overheat when operated at less than 50 per cent load. This permits only intermittent use of the ten-, three-, and one-per-cent brightness taps.

3. On the one-per-cent brightness tap, primary power factor and efficiency are excessively low, being only 22 per cent and 60 per cent, respectively, for the three-kilowatt combination tested.

4. Voltage encountered on open circuit is increased by approximately the same ratio as the current was decreased.

For comparison with resonant-regulator performance, curves showing results of tests conducted upon a conventional three-kilowatt 220-volt-input 6.6-ampere-output moving-coil regulator connected to a variable lamp load are included in Figure 1. Within the region of short circuit to rated load, it can be seen that the input current is approximately constant, and the primary power factor is nearly proportional to the load.

Resonant-Regulator Development

The first experimental resonant-circuit regulator was received by the Army Air Forces and installed in the early part of 1941. Test results and service experience proved satisfactory, and so it was decided to use resonant regulators for all future installations. The first regulator to be produced in quantity was an oil-immersed self-cooled five-kilovolt-ampere 230/115-volt 6.6-ampere unit which included five brightness-selector relays, four runway-selector relays, a power-supply relay, and an open-circuit protector relay. The brightness- and runway-selector relays were interlocked with the power relay in such a manner as to insure that the regulator would be de-energized when they were operated. This regulator was adopted as standard by the Army Air Forces (type *A*-1, specification 32360), and later standardized by the Army, Navy, and Civil Aeronautics Administration (specification *AN-R-3a*). A monocyclic square, and later a resonant *T* circuit, were used to obtain the constant-potential–constant-current transformation in this regulator.

In 1943 a 7.5-kw 2,300-volt regulator was developed in order to meet increased power demands, and to fit into the complete airport lighting system then being standardized. This regulator (specification *AN-R*-17) is the present Army,

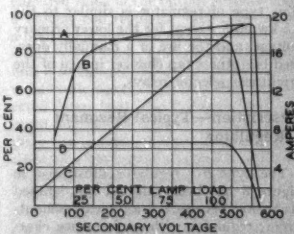


Figure 1. Moving-coil regulator, three-kilowatt, 220-volt primary winding, 6.6-ampere secondary winding

A—Primary current
B—Efficiency
C—Primary power factor
D—Secondary current

Figure 2 (left). Resonant-circuit regulator, 7.5 kw, 2,300 volts, 6.6/5.5/-4.8/4.2/3.8 amperes, remote brightness control

Figure 3. Resonant-circuit regulator, type-*B*-1, six kilowatts, 230 volts, 6.6/5.5/4.8/4.2/3.8 amperes, manual brightness control

Navy, and Civil Aeronautics Administration standard, and several hundred have been procured from two separate sources. It is illustrated in Figure 2. The 7.5-kw regulator is oil-immersed, self-cooled, weighs approximately 1,000 pounds, and includes five brightness-selector relays and one open-circuit protective relay. It is designed for use with a separate remote-controlled oil switch, and a control panel (specification *AN-P-59*) which is installed in the airport control tower.

Shortly afterwards, a requirement arose for a 230-volt manually controlled regulator for overseas installations of high-intensity runway and approach lights. This resulted in the development of the six-kilowatt regulator known as the type-*B*-1 (Army Air Forces specification 32470) which is illustrated in Figure 3. This type of regulator is similar to the 7.5-kw unit, except for the lower primary voltage, and the use of a manually operated brightness tap changer in lieu of the brightness-selector relays.

Description—Typical Resonant Regulator

The type-*B*-1 regulator illustrated in Figure 3 has been selected for detailed discussion, because it is a typical resonant-circuit regulator with performance characteristics similar to the majority of units tested. This regulator consisted of the major items shown on the wiring diagram of Figure 4, inclosed in or mounted on the front of a sheet-steel tank containing 28 gallons of oil. The complete assembly weighs 965 pounds and is approximately 24 by 29 by 31 inches high.

The essential portion of the regulator is the resonant circuit, sometimes called "monocyclic square," which consists of two five-microfarad, 1,400-volt mineral-oil capacitors (items *F*, Figure 4), and two 530-ohm 60-cycle reactors (items *E*, Figure 4). The constant-potential–constant-current transformation is performed by this circuit. It has been demonstrated mathematically that the following relation exists, assuming that there are no losses, and that all four reactances are equal in magnitude:[1]

$$I_s = \frac{jE_p}{X}$$

where

I_s = output current
E_p = input voltage
X = reactance of one side of square
j = operator denoting 90 degrees counter-clockwise rotation

Inspection of this relation reveals that output current is independent of the load, but that it is directly proportional to and 90 degrees out of phase with the input voltage. Experience with actual regulators indicates that the relation may be used with negligible error over the normal operating range. Losses in well-designed reactors and capacitors have little effect on the output current, but the reactances should be held within one per cent of the desired value (or compensated for by means of factory adjustment taps on the input or output transformer).

Table I

Brightness in Per Cent	Current in Amperes
100	6.6
30	5.5
10	4.8
3	4.2
1	3.8

The functions of the two coil 200-210-220-230/1,900-1,580-1,380-1,210-1,090-volt 6.5-kw-input transformer (item *C*) are to provide the correct voltage for the monocyclic square and to isolate the high-voltage from the low-voltage-input circuit. The tap changer (item *D*) is used to compensate for sustained variations in voltage impressed upon the monocyclic square; the five values of lamp brightness are easily obtained by means of the brightness tap changer (item *B*) which may be operated without de-energizing the regulator.

The manually operated 35-ampere circuit breaker (item *A*) provides on–off control, and open-circuit protection by means of the shunt trip which is energized through the normally closed contacts of the series relay (item *H*) when open circuit occurs. The resistor (item *J*) provides a slight time delay, thereby preventing undesirable tripping during switching.

The purpose of the two-coil 3.5/6.6-ampere, six-kilowatt-output transformer (item *G*) is to limit the open-circuit voltage. Theoretically the open-circuit output voltage of the monocyclic square would be infinite; in an actual regulator (without output transformer), it would rise dangerously high, and might cause immediate

failure of the capacitors. When the secondary winding of the regulator under discussion is opened, the monocyclic square maintains the current in the primary winding of the output transformer, the core becomes saturated, and the output voltage is limited to approximately 175 per cent of the full-load voltage.

Performance Data—Typical Resonant Regulator

The regulator illustrated in Figure 3 was subjected to extensive laboratory tests, and the results obtained are shown in Figures 5 to 9, inclusive.

The data shown in Figures 5, 6, and 7 were taken by operating the regulator on a 230-volt 60-cycle power supply with a variable lamp load, and making direct measurements of input and output current, voltage, and power. The current-regulation curves for all five brightness taps, shown in Figure 5, indicate a maximum drop in current of 3.5 per cent from short circuit to full load. Figure 6, when compared with Figure 1, illustrates the basic difference in performance between resonant and conventional moving-coil regulators. The moving-coil unit has a constant input current and a power factor which is nearly proportional to the load, while the resonant circuit unit has an input current which is nearly proportional to the load, and a power factor of unity from 25-per-cent load to full load. Figure 7 shows that the resonant regulator has excellent power factors and efficiencies even at the lowest brightness tap (3.8 amperes) whereas the moving-coil regulator would have a power factor of less than 25 per cent lagging.

The data shown in Figure 8 were taken with two regulators placed in a large cold room, connected to a 230-volt 60-cycle power supply and to a six-kilowatt lamp

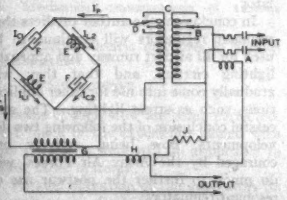


Figure 4. Wiring diagram, type-B-1 resonant-circuit regulator

A—Manual circuit breaker with shunt trip
B—Brightness tap changer
C—Input transformer
D—Primary-voltage tap changer
E—Reactor
F—Capacitor
G—Output transformer
H—Series relay
J—Resistor

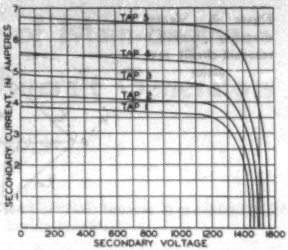


Figure 5. Current-regulation, type-B-1 resonant-circuit regulator

load. Meters were placed outside the cold room, with provision made for switching from one regulator to another. Test runs were made at several temperatures, with each temperature held constant during the test and for at least 24 hours before the test run was started. Readings were taken immediately after energizing the regulator, and the time required for the output current to reach normal room-temperature values was recorded. The two regulators, although made by different manufacturers, were quite similar in performance at room temperature. The curves of Figure 8 show very plainly that chlorinated-diphenyl capacitors are not satisfactory, unless the regulator is to be installed in a heated room.

The vector diagrams shown in Figure 9 were plotted from data taken with the regulator connected to a 60-cycle power supply held constant at 230 volts and a lamp load which was varied from short circuit to open circuit. The two diagrams are oriented so that the correct relation between corresponding currents and voltages exists. The values of currents and voltages existing in the monocyclic square under rated load conditions are shown by the solid lines, while the dotted lines show the loci of the corners of the diagrams, so that the vector diagrams for any load may be visualized. The change in voltage applied to the square due to voltage drop in the input transformer as the load is increased from short circuit to rated load is too small to be shown, but the increase in voltage due to the large leading current flowing in the input transformer at overloads is illustrated.

Resonant-Regulator Characteristics

The current regulation of the resonant-circuit regulator depends primarily upon the accuracy of tuning of the resonant circuit, and upon the regulation of the input and output transformers. Since the output current of existing regulators varies in proportion to variations in a supply voltage, it has been considered uneconomical to specify better than four-per-cent regulation (±2 per cent of the specified current), although it could be obtained without difficulty. The importance of current regulation is minimized by the fact that, after installation, the normal load current may be corrected by means of taps on the regulator input transformer, and/or adjustment of the supply voltage.

Efficiency of a resonant regulator is determined by the losses in reactors, capacitors, and transformers, and is maintained at a comparatively high value, even at light loads. Power consumed by built-in relays ordinarily is included in the regulator losses, unless supplied from separate control circuits.

Except at extremely light loads, a properly designed resonant regulator has a primary power factor which is approximately equal in magnitude but opposite in sign to the secondary power factor. For example, the input power factor of a regulator feeding a 90-per-cent-lagging series load would be approximately 90 per cent leading. The actual input power factor is determined by the following factors:

1. Manufacturing tolerance in monocyclic square.
2. Exciting current of input transformer.
3. Exciting current of output transformer.
4. Series coil of protector relay.
5. Inductive reactance of series load.

Factors 3, 4, and 5 cause leading power factors, factor 2 has a lagging effect, and the first factor may have either a lagging or leading effect.

The effect of frequency variations upon resonant-circuit regulators is much less than one would expect at first thought. The regulator illustrated in Figure 3 has been used satisfactorily on 50-cycle power supplies without modification. The output current at full load is approximately three per cent less on 50 cycles than it is on 60 cycles.

Oscillographic studies indicate that the output current from a resonant regulator operating near full load has no switching surges. This is in direct contrast to the effective value of the output current from a moving-coil regulator, which surges to a high value and then oscillates about the steady-state value, immediately after the unit is energized. Observations made on a monocyclic square regulator operating at rated lamp load also indicate that the input and output current waves approximate sine waves. Although time limitations have prevented a complete study of harmonics under all load conditions, no trouble due to harmonics has been reported during four years operating experience with loads consisting of lamps, and lamps connected to well-designed isolating transformers.

Summary

The satisfactory service obtained from over 1,500 resonant regulators procured

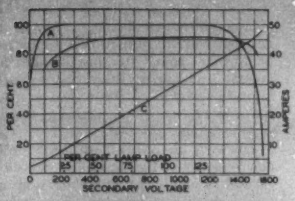


Figure 6. Performance data, brightness tap 5, type-B-1 resonant-circuit regulator

A—Primary power factor
B—Efficiency
C—Primary current

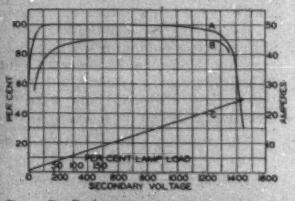


Figure 7. Performance data, brightness tap 1, type-B-1 resonant-circuit regulator

A—Primary power factor
B—Efficiency
C—Primary current

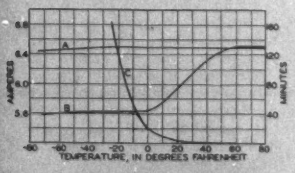
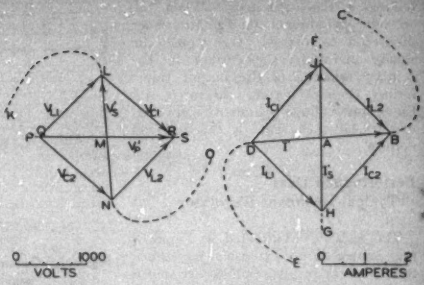


Figure 8. Low-temperature performance, resonant-circuit regulators

A—Initial output current, resonant regulator with mineral-oil capacitors
B—Initial output current, resonant regulator with chlorinated-diphenyl capacitors
C—Time required for output current of regulator with chlorinated-diphenyl capacitors to reach rated value

since 1940 is evidence that this type of regulator has moved out of the experimental category. Resonant regulators are the most satisfactory means of providing power for airport runway and approach lighting circuits, which must be operated at reduced intensities on clear nights, and they have been standardized by the Army, Navy, and Civil Aeronautics Administration. Moving-coil regulators still are used for applications where operation at reduced intensities is not required, such as street lighting and airport boundary lighting.

Figure 9. Vector diagram, type-B-1 resonant-circuit regulator



Voltages:
As load is increased from short circuit to rated load:
Point *L* moves from *M* to *L*
Point *N* moves from *M* to *N*
As load is increased from rated load to open circuit:
Point *L* moves from *L* to *K*
Point *N* moves from *N* to *O*
Point *R* moves from *R* to *S*
Point *Q* moves from *Q* to *P*

Currents:
As load is increased from short circuit to rated load:
Point *B* moves from *A* to *B*
Point *D* moves from *A* to *D*
As load is increased from rated load to open circuit:
Point *B* moves from *B* to *C*
Point *D* moves from *D* to *E*
Point *J* moves from *J* to *F*
Point *H* moves from *H* to *G*

Existing resonant-circuit regulators have the following definite advantages and disadvantages:

A. Advantages:

1. No moving parts (except relays).
2. Unity power factor with resistance loads, leading power factor with inductive loads.
3. High power factor and efficiency maintained with loads as low as 20 per cent. This permits satisfactory operation of lighting circuits at one-per-cent brightness.
4. Brightness control easily obtained by varying input voltage to resonant circuit.
5. No switching surges of sufficient duration to affect lamp life.

B. Disadvantages:

1. Output current varies with input voltage.
2. Not familiar to most operating and maintenance personnel.

In contrast to the foregoing, moving-coil regulators have the following characteristics:

A. Advantages:

1. Output current constant regardless of primary voltage.
2. Conventional equipment, familiar to most electrical personnel.

B. Disadvantages:

1. Moving parts which require accurate adjustment.
2. Power factors of 75 to 85 per cent lagging at full load, unless supplied with capacitors for power-factor correction.
3. May not be used at less than 50-per-cent load, owing to overheating.
4. Unsatisfactory for brightness control, owing to overheating, and extremely low power factors and efficiencies at low brightnesses.
5. Current surges immediately after energizing shorten lamp life, especially for airport use where frequent switching may be required.

Sufficient data for an accurate cost comparison of the two types of regulators are not available, owing to the fact that all resonant regulators procured to date included an input transformer and brightness tap-changing equipment. Elimination of these items, however, should make the cost of a resonant regulator equal to or less than the cost of a moving-coil regulator.

In conclusion, the author predicts that resonant regulators will continue to be used for all airport runway and approach lighting circuits, and that they will gradually come into use for other applications, such as street lighting. The successful conclusion of the following two developments, now being actively encouraged by the Army Air Forces, will do much to further the postwar use of resonant regulators:

1. A lightweight air-cooled design.
2. A method of compensating for primary-voltage variations.

Reference

1. Theory and Calculation of Alternating-Current Phenomena (fourth edition). Charles Proteus Steinmetz. McGraw Publishing Company, 1908. Pages 78–129.

Parallel Operation of Main-Engine-Driven 400-Cycle Aircraft Generators

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MEMBER AIEE

Synopsis: This paper reports progress in the development of variable-ratio drives and governors for parallel operation of aircraft alternators driven from the main engines. Preliminary tests have been made demonstrating successful parallel operation of such drives under various conditions of acceleration and loading. The general system of operation and results of some of the first tests are described in this paper.

POTENTIAL military requirements may create a demand for very large aircraft. Four-hundred-cycle three-phase 208Y–120-volt a-c power appears to be quite suitable for most of the electrically operated devices. The electrical manufacturers in this country have been asked by the Army Air Forces to develop an electric system to generate, distribute, and utilize this power to perform various required functions on such aircraft.

For reasons of space, weight, economy, and reliability, it was decided to drive these generators from the main engines. Several other means of driving such generators were considered, but because of the very limited time available for the development this method was selected, as it appeared to hold most promise for a quick solution. Among the other means considered were:

1. Auxiliary engines or gas turbines.
2. Exhaust-gas turbines.
3. Waste-heat boilers and steam turbines.
4. Hydraulic torque converters.
5. Mechanical transmissions of various types.
6. Rotating electric machines in various combinations.
7. Electronic means.

Some of these now are being perfected, and much of the experience gained with the present systems will be applicable to these other systems.

Parallel operation of the generators on a multiengine airplane is desired for military service, because it provides the following benefits:[1]

1. Greater motor-starting capacity.
2. Reduction of time and magnitude of voltage disturbance from fault, motor starting, or loss of generation.
3. More effective use of spare capacity, so that smaller or fewer generators can be used without excessive load-transfer switching.
4. Greater ability to withstand fault without disruption of service and greater ability to burn faults clear.
5. Continued operation of load equipment following engine or generator failure; does not require any automatic-transfer equipment nor any immediate attention from the operator.

Statement of the Problem

The aircraft engines are relatively large compared with the generators, as they are used for main-propulsion power. Consequently, their rating may be from 50 to 100 times the rating of the generators which are used for auxiliary electric power on the airplane. In addition the main-engine speed may vary over a wide range (three to one or more), depending upon the conditions of flight. Furthermore, all engines are not always operated at equal speeds at all times. These factors presented several new problems to the electrical industry.

Parallel operation of a-c generators is common in industrial or central-station practice. However, usually most of the following conditions prevail for constant-frequency a-c systems with generators operated in parallel:

1. The prime mover is comparable in rating with the generator.
2. The prime mover usually is operated at constant speed.
3. The prime mover is governed to operate in accordance with the requirements of the generator.
4. All prime movers on the system are operated at a speed exactly proportional to the system frequency.
5. Transient speed changes of the prime movers are relatively small.

In contrast with this, in the proposed aircraft system:

1. The prime mover is large, frequently being 50 to 100 times the rating of the generator.
2. The prime movers are operated over a wide speed range to meet changing conditions of flight.
3. The prime mover is governed to operate in accordance with the propeller and propulsion requirements of the airplane.
4. Different engines on the same airplane may be operated at different speeds at the same time.
5. Transient speed changes of the prime movers may be very rapid.

The problem is, with this combination of conditions, to provide a means of driving the alternators from the main engines, maintaining frequency and voltage at all times, and keeping all the machines operating in synchronism and sharing the load. Of course, in addition to these fundamental requirements the system must be suitable for use in aircraft, which conditions bring in a host of additional requirements which have been listed elsewhere.[1]

The alternators now in use have eight poles and operate at 6,000 rpm to deliver 400 cycles. This means that one mechanical degree is equivalent to four electrical degrees. Thus to maintain synchronism it is necessary that the mechanical displacement among generators does not exceed about 20 mechanical degrees, and to divide load properly they should be within one or two mechanical degrees of each other. This close relationship should be maintained, even though the individual engine speeds vary widely and are subject to high rates of acceleration. To the uninitiated, it looks like an impossible job, except with some type of slip device such as a fluid coupling. A slip device is out of the

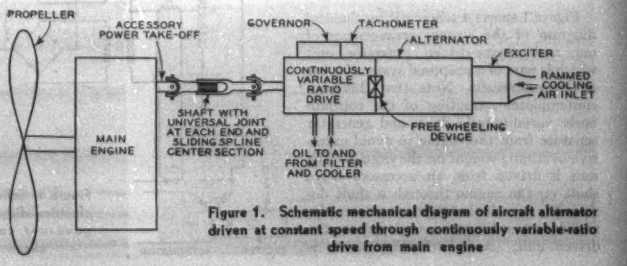

Figure 1. Schematic mechanical diagram of aircraft alternator driven at constant speed through continuously variable-ratio drive from main engine

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The author wishes to express his appreciation for their cooperation in carrying on these experiments and to the engineers of the Sundstrand Machine and Tool Company for providing the variable-ratio drive units.

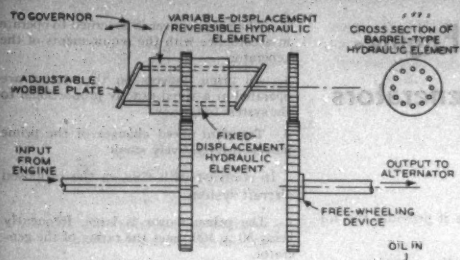


Figure 2. Schematic mechanical diagram of one form of continuously variable-ratio-drive unit

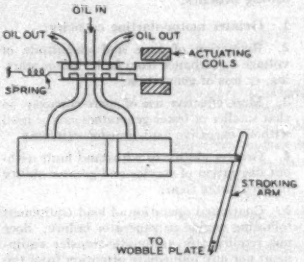


Figure 3 (below). Schematic mechanical diagram of governor and servo mechanism

question, however, because of the wide speed range involved, which makes it too inefficient to be applicable. The use of a positive-displacement type of drive to improve efficiency requires the development of a high-speed governor.

For constant frequency to be obtained from conventional generators the latter must be operated at constant speed. This means that, if the prime mover has a variable speed, some type of variable ratio transmission must be interposed between the prime mover and the generator and governed to provide the desired result.

Procedure

An analytical approach[3] provided specifications for governor design and indicated that the characteristics required for parallel operation were well within practical design values and that parallel operation could be achieved.

It was necessary to overcome many obstacles, and some are yet to be mastered. Nevertheless, the fundamental principles of accomplishing this job have been established and demonstrated.

Because the solution of this problem required the development of a governing system with a very high speed of response, it was thought that many engineers would be interested in a description of the general method of accomplishing this result. The purpose of this paper is to give a brief description of the governor and what is believed to be the first 400-cycle a-c system of this type which has been successfully demonstrated.

Description of the System

Figure 1 shows a schematic mechanical diagram of the system arrangement of one main-engine-driven generator unit which is part of a proposed system for use on large aircraft. Note that this plan contemplates mounting of the continuously variable-ratio drive and generator separate from the engine to avoid excessive overhung weight on the engine. The unit is driven from an accessory drive shaft on the engine through a shaft designed to permit the engine to move in its resilient mounting without injury to the driven unit. A free-wheeling device is located between the variable-ratio drive and alternator, which permits driving the alternator but never permits the alternator to try to drive the engine. The governor adjusts the ratio of the variable-ratio drive to maintain frequency and load division, as explained later, in spite of variations in engine speed.

The setup used in test differs from Figure 1 in that the driving power was taken from the main output shaft of the engine through a suitable gear box, as the accessory drive shafts on these engines were not large enough to provide the required power.

Figure 2 is a schematic mechanical diagram of one form of continuously variable-ratio drive unit. This unit is a differential type of hydraulic drive using oil as the working medium. A simple valve arrangement (not shown) is located between the pump and motor end of the unit, providing a properly valved path for the flow of the working fluid between the pump and motor.

The input end of the unit has a variable stroke. This stroke is varied by the angle of the wobble plate, which in turn is positioned by the governor. The output end of the unit has a fixed stroke. Thus the angle of the adjustable wobble plate on the input end of the unit establishes the relative speed of the fixed stroke element with respect to the variable displacement element. When the stroke of the latter is zero, both elements are locked hydraulically and rotate as a unit. This is the straight-through drive ratio. At this ratio hydraulic losses in the unit are at a minimum. The variable-ratio drive unit should be designed to have maximum efficiency at engine speeds corresponding to the cruising speed of the airplane.

Figure 3 is a schematic mechanical diagram of the governor and servo mechanism which operates to position the wobble plate and thereby adjusts the drive ratio to provide the desired output speed.

Oil at a moderate pressure is supplied to an electromagnetically operated pilot valve, which is balanced against a spring. A valve movement of a few thousandths of an inch permits oil to enter one side of the piston and leave from the other side, thus causing the piston to move. The piston is linked mechanically to the wobble plate of the variable-ratio drive. As a result of the very small valve movement required, and by proper design of the ports, a very high speed of response is achieved. The pilot valve position is governed by the electrical signal introduced into its actuating coil. The governor uses a constant-current balanced-valve system. The pilot valve always returns to its neutral position after the speed correction is made. The transient position of the valve is determined by the change in signal above or below the balance-position signal.

Figure 4 is a schematic electrical diagram of the governor control circuit showing the principle of operation. For

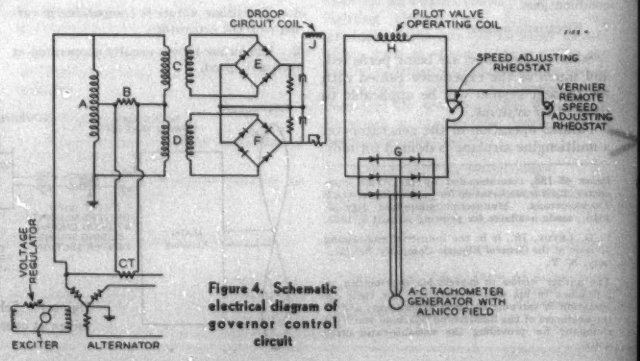


Figure 4. Schematic electrical diagram of governor control circuit

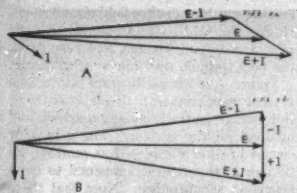


Figure 5. Vector relations in load-frequency droop circuit

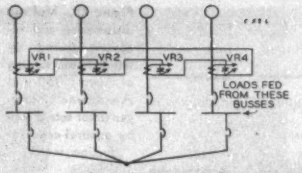


Figure 6. Typical star bus arrangement showing current-transformer connections for differential cross-current compensation for division of reactive load among generators

simplicity certain other circuits including stabilizing and emergency overspeed circuits are not shown.

The operation is as follows: A small a-c tachometer generator using a permanent-magnet field is driven from the output of the variable-ratio drive. The output of this tachometer is rectified by rectifier *G* and applies a signal, which is directly proportional to speed on the operating coil *H*.

Another signal, which is proportional to load, is placed on droop-circuit coil *J*, which is wound on the same core as *H*. This provides a five-per-cent frequency droop at full load. This load-frequency droop causes the generators to share the kilowatt load when operating in parallel.

The load–frequency-droop signal is derived from a circuit which is sensitive to the inphase component of current. This provides a signal approximately proportional to power load on the alternator and is accomplished in the following manner. Terminal voltage of the alternator is fed into a midtapped autotransformer *A*. Another signal, which is proportional to current, is obtained from a current transformer and fed into the resistor at *B*. This latter signal is added and subtracted vectorially from the voltage signal, the results of the addition and substraction appearing in transformers *C* and *D* respectively. The outputs of these transformers are rectified by full-wave dry-type rectifiers *E* and *F*. The resulting two d-c signals are subtracted, and their difference placed on the droop-circuit coil *J*.

Figure 5 shows the vector relations involved in the load–frequency-droop circuit.

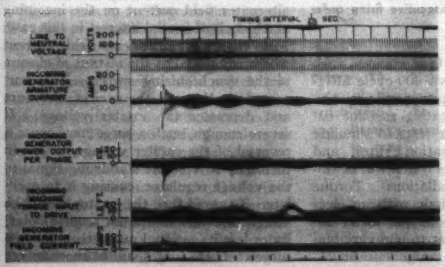
Figure 5a shows the condition with a lagging power-factor load. Note that there is a substantial difference between the voltage vectors $E + I$ and $E - I$, which provides a signal to the droop coil.

Figure 5b shows the condition with a zero power-factor load. Here $E + I$ and $E - I$ are equal, hence their difference is zero, and no signal is introduced into the droop coil.

The droop circuit is responsive to real power and not to reactive power.

The division of reactive kilovolt-amperes among several generators connected in parallel can be achieved by means of differential cross-current compensation in the voltage-regulator circuits. This provides for reactive division without voltage droop. Schematically this connection is shown in Figure 6. A normally closed interlock is provided on each generator circuit breaker to short-circuit its reactive division current transformer when the circuit breaker is open and the generator is taken out of service.

This differential reactive-division circuit is ideal for parallel operation, providing the units are to operate in parallel at


TIMING INTERVAL 1/5 SEC
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INCOMING GENERATOR ARMATURE CURRENT
INCOMING GENERATOR POWER OUTPUT PER PHASE
INCOMING MACHINE TORQUE INPUT TO DRIVE
INCOMING GENERATOR FIELD CURRENT

Figure 7. Synchronizing disturbance with incoming machine at full voltage with no load on system

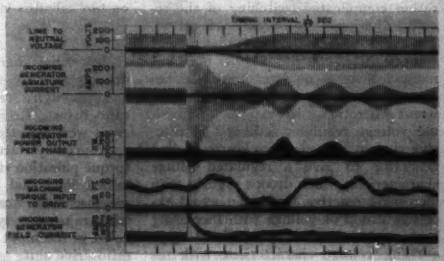

TIMING INTERVAL 1/5 SEC
LINE TO NEUTRAL VOLTAGE
INCOMING GENERATOR ARMATURE CURRENT
INCOMING GENERATOR POWER OUTPUT PER PHASE
INCOMING MACHINE TORQUE INPUT TO DRIVE
INCOMING GENERATOR FIELD CURRENT

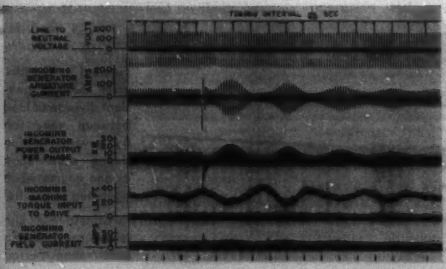
Figure 9. Synchronizing disturbance with incoming machine at full voltage and both incoming and running machines carrying load

Figure 10 (below). Synchronizing disturbance with incoming machine running unexcited

Arrow indicates time of closure of exciter field switch

Figure 8. Synchronizing disturbance with incoming machine at full voltage and both incoming and running machines carrying load

Incoming machine purposely synchronized 180 electrical degrees out of phase with running machine


TIMING INTERVAL 1/5 SEC
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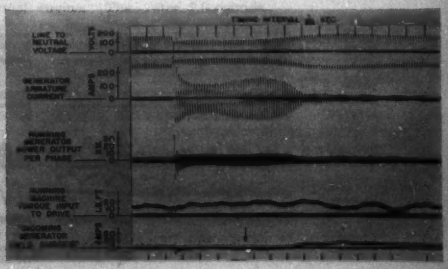
INCOMING GENERATOR FIELD CURRENT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GENERATOR ARMATURE CURRENT
RUNNING GENERATOR POWER OUTPUT PER PHASE
INCOMING MACHINE TORQUE INPUT TO DRIVE
INCOMING GENERATOR FIELD CURRENT

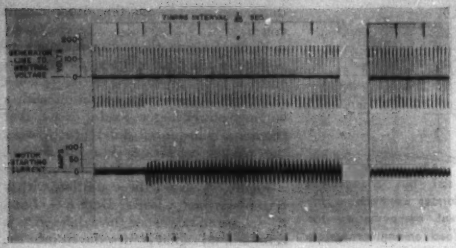

Figure 11. Voltage disturbance and recovery caused by simultaneous starting of two 750-watt Amplidyne motor-generator sets driven by squirrel-cage induction motor

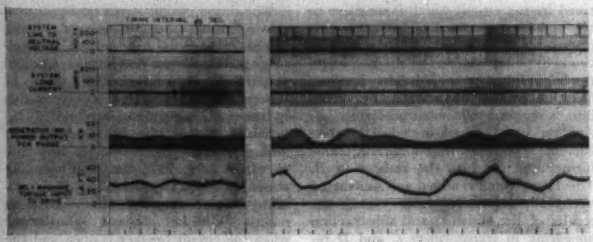

Figure 12. First section of oscillogram shows normal parallel operation with smooth engine, and second section shows effect of making engine rough by short-circuiting spark plugs on two cylinders in consecutive firing order

all times. If, however, nonparallel operation is desired, or operation with the system split into various combinations other than all machines operating in parallel, a rather complicated switching of the reactive-division control circuits is involved. To avoid this, individual cross-current compensation can be used. For this method there is no interconnection between reactive-division circuits for different generators. Instead, each individual voltage regulator is biased by reactive current output of its corresponding generator to give a regulated-voltage characteristic which droops slightly with increasing reactive load. To avoid excessive droop of voltage with increasing load, compensation can be added to give a rising voltage characteristic with resistive load and the combination designed to hold substantially flat voltage at the average load power factor.

Operating Experience

Tests have been made with a laboratory setup using two 450-horsepower air-cooled radial aircraft type engines, each driving a 30-kw 40-kva 400-cycle alternator through a step-up gear and variable-ratio drive. Reciprocating gasoline engines were selected for tests to simulate appropriately acceleration rates and torque pulsation effects which will be obtained in actual installations. Torque measurements were made with an electric-strain-gauge-type torque meter located in the input shaft to one variable-ratio drive unit.

The presence of the free-wheeling between the alternator and drive was found to make synchronization very easy even with purely random synchronization. The machines have been synchronized at random at full voltage with and without load at widely different speeds. They also have been synchronized with the incoming-machine exciter field circuit open, closing the field simultaneously with the generator circuit breaker and permitting the field to build up while synchronizing.

Figure 7 is an oscillogram showing a typical synchronizing disturbance with full voltage on the incoming machine and no load on the system. The generator circuit breaker was closed at random, although in this case it happened to close nearly in synchronism. Note that there is very little disturbance to the system voltage. With automatic speed matching and synchronizing equipment, equal or better performance could be achieved consistently.

Figure 8 is an oscillogram showing a synchronizing disturbance similar to Figure 7, except that both machines had an initial load on them prior to synchronization.

Figure 9 is an oscillogram showing a synchronizing disturbance on the two generator system with each generator carrying load at normal voltage, and with the synchronizing switch purposely closed when the generators are 180 electrical degrees out of phase. At the instant of closure this corresponds to a three-phase short circuit on both machines with correspondingly high armature currents. The machines pull into step, and system voltage has recovered in 0.1 second.

The lower trace on Figure 9, showing alternator field current on the incoming machine, is of special interest in this case. Note the high transient field current which is induced at the instant of closure of the synchronizing switch. This current flows through the exciter armature and depresses the exciter voltage. If severe enough, such a surge may cause a reversal of the exciter voltage, which in turn may reverse the stabilizing signal to the voltage regulator, causing it to oscillate. To avoid this, the exciter should be designed so that it will not reverse polarity or lose its residual magnetism on such surges. These surges will be more severe on a system with more generators and with running loads.

The power trace indicates that the generator is free-wheeling for a short interval as the machine is pulling into step. The drive input torque does not go negative, however, as the generator is free-wheeling and the drive losses are supplied

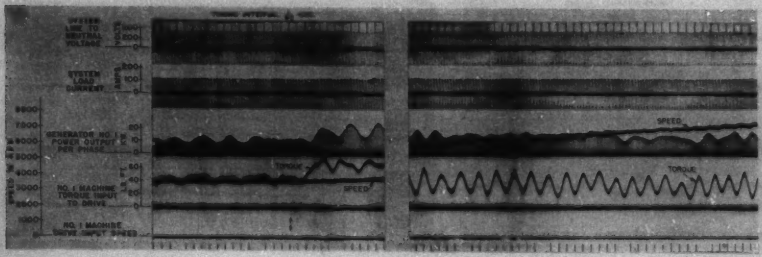

Figure 13. Oscillogram showing transient division of load between generators by governor action during acceleration of one engine when operating in parallel

Accelerating engine is very rough during accelerating period

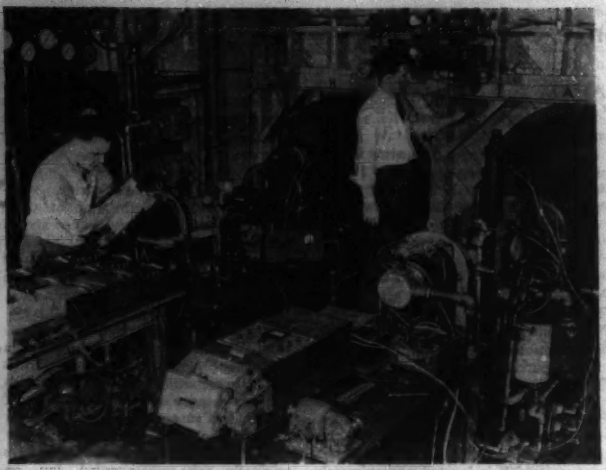

Figure 14 (above). General view of test setup

Driving engines are located behind wall

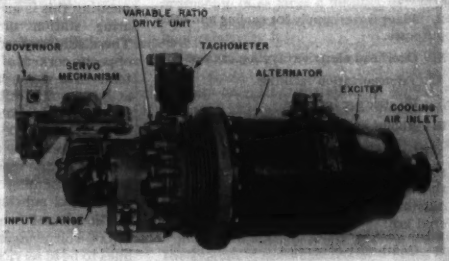

Figure 15. Side view of combined variable-ratio drive and alternator used in tests

chines are operating in parallel. The accelerated engine was very rough during the accelerating interval in this case. Acceleration begins at the time indicated by the double-headed arrow. The oscillogram was shortened for reproduction purposes, and the portion between the two parts shown represents a time interval of 1.4 seconds. The rate of acceleration is about 1,700 rpm per second at the input to the accelerated drive. Note that the machines remain in step and that, though the accelerated machine picks up load initially, the governor reduces the load even before the acceleration is completed.

The oscillograms presented here] are typical of more than 100 oscillograms which have been taken under a great variety of conditions in exploring the effect of various factors and combinations of conditions.

Figure 14 is a general view of the test setup. The engines are behind the wall and are coupled directly to the gear boxes which in turn are coupled to the variable-ratio drives which drive the alternators.

Figure 15 is a side view of an early design of one of the variable-ratio drive units and alternators used for these tests. This particular unit is rated 50 horsepower continuous and has an input speed range of 2,700 to 7,000 rpm. The over-all length of the combined unit is 29 inches, and the weights are as follows: alternator and exciter, 78 pounds; variable-ratio drive, 55 pounds; governor and servo mechanism, nine pounds; tachometer, 2.9 pounds.

Final designs have not been completed, and efficiency and life tests have not been run. However, these tests are planned for the near future. It is expected that these new variable-ratio drive units will weigh about 70 pounds and have a maximum efficiency of about 85 per cent. The new units will cover a wider speed range and be rated to correspond with the continuous and overload ratings of the generator.

This test program should contribute much data which will help to evaluate the a-c system for aircraft.

by the input shaft. The power and torque curves pulsate for a few cycles as the generators oscillate about their equilibrium position, but no destructively large torques appear during the synchronization in this case.

Figure 10 is an oscillogram showing the disturbance resulting from bringing the incoming machine on the bus running at approximately full speed but unexcited. In this case the exciter field switch was closed slightly later than the alternator armature switch at the time indicated by the arrow. There was no load on the system in this case. When the incoming generator switch is closed, the incoming machine operates as an induction motor running light, taking magnetizing current from the line, but practically no power. (See power trace.) When the exciter field switch is closed, the exciter of the incoming machine builds up, pulling the machine into step and furnishing its own excitation so that the circulating current drops to practically zero. The bus-voltage disturbance would be substantially less with more generators on the system.

Figure 11 is an oscillogram showing voltage disturbance and recovery from a suddenly applied load. In this case two generators were running in parallel at no load, and two squirrel-cage induction motors, each driving a 750-watt Amplidyne generator were started simultaneously. There is a momentary voltage dip of about four per cent and the voltage is restored to normal in about 0.05 second. The induction-motor Amplidyne sets accelerated to full speed in about 0.7 second, and, as the Amplidynes were unloaded, the induction-motor current dropped to exciting current only. The oscillogram was shortened for reproduction purposes, and the portion between the two parts shown represents a time interval of 0.6 second.

This oscillogram gives some idea of the nature of voltage disturbances resulting from switching loads an the system. With more generators on the system, the disturbance would be less for a given load increment.

Figure 12 is an oscillogram showing two machines operating in parallel. The first part of the oscillogram shows normal operation with a normal engine. The second part of the oscillogram shows the effect of purposely making one engine rough by short-circuiting spark plugs on two cylinders in consecutive firing order. Note that the power division between generators pulsates but that, even in this severe case, the generator does not freewheel. The system load current and voltage are influenced only slightly. In a four-engine set the influence on the system would, of course, be less.

Figure 13 is an oscillogram showing transient division of load during an acceleration of one engine, when the ma-

Electric Power in a Steel Plant

R. W. GRAHAM
MEMBER AIEE

IF ALL THE APPLICATIONS of electricity were listed, it would be found that this servant of man is used more extensively and in a greater variety of applications in the manufacture of steel than in any other industry. From the tiny photoelectric cell to the giant slow-speed reversing rolling-mill motor delivering torques of 2,000,000 pounds at one-foot radius, the application of electric power with its ease of control in the manipulation of steel is amazing as well as fascinating to anyone.

The use of electric power to replace hand labor and other less efficient methods of power supply has been most pronounced in the following applications in a steel plant:

1. Material handling, as coal and ore unloading.
2. Plant water supply for cooling and other purposes.
3. Overhead electric traveling cranes.
4. Transportation facilities.
5. Electric arc furnaces.
6. Rolling-mill drives.

Electric-power requirements in the steel industry are more demanding than those in many other industries. The two outstanding requirements to be considered are:

1. Continuity of service.
2. Methods and equipment to eliminate interruptions.

It is well known, that, when large tonnages of steel are in the process of pouring or rolling, an interruption of minutes and even seconds may in some instances make it necessary to scrap the entire mass of steel which is being processed. Because of the rapid drop in the working temperature of the steel there is always the question, after the restoration of a short power interruption, whether to attempt to roll the steel then in the mills or to take the loss in tonnage, as the bar of steel is then too long to be reheated in the soaking pits.

For adequate protection against power interruptions there are generally two or more sources of current supply. The Bethlehem Steel Company plant in Lackawanna has two outdoor substations with a combined capacity of 70,000 kva receiving 60,000-volt 25-cycle power over two transmission lines from the Niagara system, which is located approximately eight miles from the plant. Supplementing this is an auxiliary steam-generating station of 20,000-kw capacity. These stations feed into a tie network on opposite corners of a rectangular loop system. The steam station generates energy at 6,600 volts while the power purchased from the public utility system is stepped down from 60,000 to 6,600 volts, which gives a complete 6,600-volt distributing system for the main power supply to the larger consuming units and to the departmental substations.

The normal operation of the Niagara 60,000-volt system is for both incoming lines to be in service with oil circuit breakers at both ends of the line and a tie circuit breaker between them. These lines are tee-taped to the 20,000-kva transformer station which feeds the strip and bar mills through selective switching, permitting either line to feed the mills.

Because of the large number of synchronous motors on the Ward-Leonard-control motor generator sets and the synchronous motors on large mill drives, a leading power factor easily can be obtained on the system.

The Bethlehem Company has 2,250-horsepower synchronous motors on motor generator sets starting directly across the line (6,600 volts) with an inrush of 9,500 kva and with a voltage drop no more noticeable than starting through reactors of the 8,500-horsepower synchronous motors, which drive 6,000-kw motor generator sets. It also has a 1,000-horsepower squirrel-cage induction motor on a mill-scale-breaker drive, starting directly across the line at 6,600 volts. These machines have special bracing to withstand the heavy inrush of across-the-line starting. Elimination of reduced voltage starters simplifies the switchgear required for these units.

The amount of energy back of this system together with the synchronous machines operating in the plant, confined in such a congested area, allow short circuits of a high magnitude. These short-circuit currents require oil circuit breakers of 500,000-kva rupturing capacity to clear faults when they occur.

The outdoor substation transformers originally were water-cooled, but, on account of the excessive cost of filtered water, they have been changed to air-cooling and provided with blowers. This eliminates the danger of failure due to freezing or leakage in the water system, which might contaminate the transformer oil. The larger transformer installations comprise three single-phase units in delta. In case of trouble in any unit, operation can be continued on open delta at reduced capacity until such time as the transformer giving trouble has been repaired.

In addition to the split-up in the main Niagara power supply to the larger consuming units, which probably represents 75 per cent of the load, the steam-generated power supply has been split into two branches, the regular load bus, *B*, and the emergency bus load, *A*. In case of Niagara power failure or trouble within the plant, the load bus *B* is dropped immediately by relaying, and bus *A* is kept alive from the steam-station source.

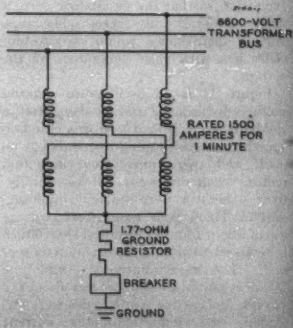

Figure 1. Three-phase zigzag grounding transformer

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Conclusions

The operation of 400-cycle a-c alternators for the supply of auxiliary power in large aircraft, driven from the main engines through variable ratio drives, is feasible, and parallel operation of these alternators is practical. No elaborate synchronizing equipment is required. Thus, the use of higher-voltage alternating current now can be considered as another form of electric power supply for large aircraft, and we can begin to evaluate its properties in a realistic manner.

References

1. BASIC CONSIDERATIONS IN SELECTION OF ELECTRIC SYSTEMS FOR LARGE AIRCRAFT, W. K. Boice, L. G. Levoy, Jr. AIEE TRANSACTIONS, volume 63, 1944, June section, pages 279–87.

2. GOVERNOR REQUIREMENTS FOR AIRCRAFT ALTERNATOR DRIVES, W. K. Boice, L. G. Levoy, Jr. AIEE TRANSACTIONS, volume 64, 1945, July section, pages 534–40.

This emergency bus *A* furnishes power to steam-plant auxiliaries such as boiler induced-draft fans, forced-draft fans, and powdered-fuel drives.

The steam station normally is supplied with surplus gas from the blast furnaces, fed to the boilers as fuel. This is supplemented with an auxiliary powdered-coal and fuel-oil supply. The emergency bus *A* also takes care of boiler-room auxiliary drives, exciters, and plant water supply.

The water supply in a steel plant is particularly important. It must be maintained constantly for cooling purposes, in the blast-furnace hearths, in the charging doors and valves of the open-hearth furnaces, in the gas scrubbers, and in many other applications where high temperatures are encountered.

The emergency bus *A* also supplies power to a few motor generator sets which furnish d-c power to open hearths and coke ovens. This d-c power must be a dependable supply, as the open-hearth cranes may be handling hot molten metal, and the coke oven machinery may be pushing hot coke, which cannot be interrupted without damage to the large pusher rams.

An industrial plant with its large integrated power system is quite similar to a public utility, except that the distances between consumers are very short.

In general the transmission system consists of several three-phase 500,000-circular-mil or 1,000,000-circular-mil copper cables supported on steel towers with wide spacing to prevent the conductors from whipping together under unfavorable wind and sleet conditions. Wide spacing is permissible with the heavy conductors, as both the supporting steel spans and the distances between the various mills are short, and with 25-cycle current line reactances are not objectionable.

Due to the proximity of the various mills and substations, it is rather difficult to set up any relaying scheme with the time elements necessary to give much selection in clearing the various lines in the system. Recent relay developments have been applied from time to time, but it is hard to keep up with advancements made in relay protection.

Relays

The original relay installation in our plant for line protection made use of *CZ* impedance-distance relays. These did not prove satisfactory, due to the relatively short lines and high currents involved, and they have been replaced with various other types, the purpose of which is to sectionalize the plant by clearing a section of the power system rather than an individual line. This is a simpler scheme and does not involve the coordination of as large a number of relays, and yet outages due to line troubles are kept relatively low.

In order to provide still better protection for the equipment, grounding transformers have been installed, as shown in Figure 1, to establish a definite ground neutral and provide adequate ground current for ground relaying. The relaying system thus is divided into two parts:

1. Phase-to-phase fault relaying.
2. Phase-to-ground fault relaying.

With the normal power system setup, the system is sectionalized into zones by means of relays, as shown in Figure 2. In case of a fault in zone 1 it is separated from zone 2 by means of overcurrent phase relays, type *IAC*, and directional overcurrent ground relays, type *CR*, at *D*89 and *D*90. Within zone 1 further separation on lines 89 and 90 is obtained by means of directional overcurrent relays, type *IBC*, and directional ground relays, type *ICC*, at *BB*89 and *A*90. Lines 98 and 99 between the hot-mill and the cold-mill busses are protected by type *IJD* pilot-wire relays, which function on either a phase or ground fault between the ends of the line while being inoperative on a through fault beyond the ends of the lines.

Pilot-wire, type *HCB*, relays are installed on lines 101 and 102 to the bar mill. The *HCB* relay takes the current in each end of the line and passes it through a positive- and zero-sequence network in each relay. The voltages across these networks are compared and are equal and opposite for any through fault beyond the line terminals. For either a phase or a ground fault between line terminals, these voltages are not equal and opposite but add up to operate

ϕ—Phase-to-phase-fault protection
GR—Ground-fault protection
HCB—Westinghouse type *HCB* pilot-wire relay
IAC—General Electric Company induction overcurrent relay
CO—Westinghouse induction overcurrent relay
IBC—General Electric Company directional overcurrent relay
CR—Westinghouse directional overcurrent relay
IJD—General Electric Company pilot-wire relay
ICC—General Electric Company current polarized ground directional relay
CWC—Westinghouse current polarized ground directional relay

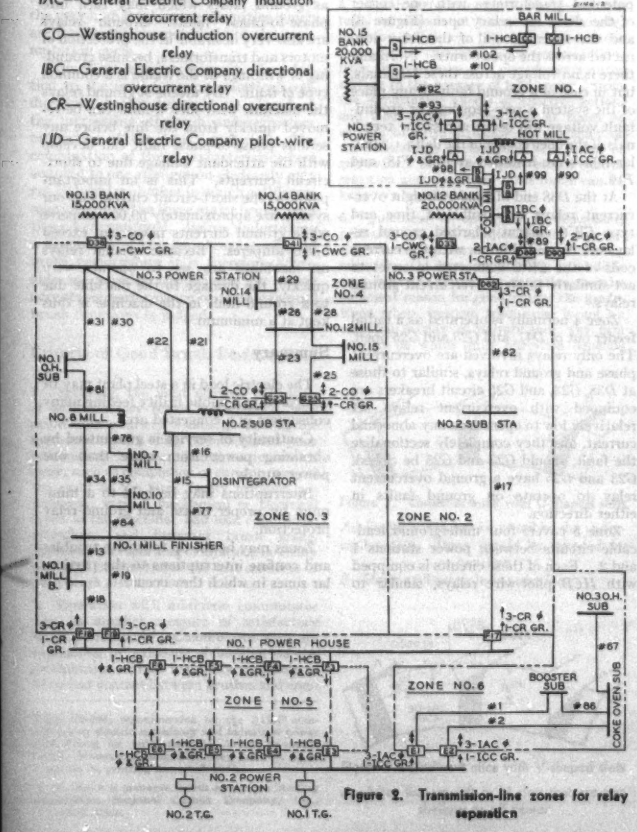

Figure 2. Transmission-line zones for relay separation

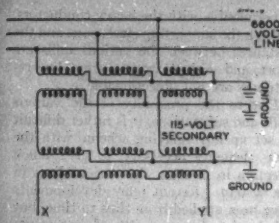

Figure 3. Potential connections for *CR* directional ground relays

relays at both ends of the line, thus clearing the faulted section.

In the original installation the 6,600-volt strip-mill substation consisted of one solid line of 24 metal-clad oil circuit breakers. After a failure of an oil switch which ruptured its tank and started a fire which destroyed several units, the bus was split into three sections, with a reactor placed between two sections and a third section relocated closer to the apparatus which it served.

All the 6,600-volt machines operating in this section of the plant are of recent design, with neutrals brought out with a double set of current transformers arranged for differential-relay protection as well as for protection from overload, phase failure, or undervoltage.

Surge protection equipment consisting of capacitors and Thyrite arresters is located in pockets in machine foundations as close as possible to the machine leads.

When the station was rebuilt, a reactor of three-per-cent reactance on 10,000-kva base was installed to reduce the asymmetrical amperes on a short circuit from 81,000 to 63,600 amperes under the worst conditions. Cross-differential protection was installed on both sections of the two hot-mill busses, and differential protection was installed on the cold-mill bus at the time of this change-over.

*A*92 and *A*93 circuit breakers are operated by straight overcurrent relays, type *IAC* on phase faults, and by ground directional relays, type *ICC*, for ground faults. This is a current-polarized relay obtaining its directional characteristic from a second current winding which is energized by the ground current flowing in the neutral of grounding transformer 30 at power station 5. The same type of relay is used for ground protection at *A*90. These ground relays operate to clear faults away from the bus.

Zones 2 and 3 separate from the rest of the system by means of directional overcurrent relays, acting as phase relays and ground relays and operating when the fault is within the zone. A typical case would be at *F*17 where there are three type-*CR* phase relays and a low-energy *CR* ground relay for protection. These relays consist of a directional element operated from phase current and voltage and an overcurrent element. The relays operate only:

1. When the direction of the current is proper.

2. When the amount of current exceeds the setting.

The ground relay is similar, but the potential for the directional element is supplied from a set of star–delta-connected potential transformers with one corner of the delta secondary open (Figure 3) and the potential coil of the relay connected across the open corner. Normally there is no voltage across these terminals, but in case of a ground fault at any place of the system a zero-sequence or ground-fault voltage will occur across the terminals of the open corner of the delta. Similar relays are installed at *D*62, *F*18, and *F*19.

At the *D*38 end of zone 3 straight overcurrent relays with sufficient time and type *CWC* current-polarized ground relays are depended upon, with the current coils of the *CWC* connected in series to act similarly to plain overcurrent ground relays.

Zone 4 normally is operated as a radial feeder out of *D*41, and *G*23 and *G*25 open. The only relays involved are overcurrent phase and ground relays, similar to those at *D*38, *G*23, and *G*25 circuit breakers are equipped with overcurrent relays set relatively low to operate on any abnormal current, and they completely sectionalize the fault, should *G*23 and *G*25 be closed. *G*23 and *G*25 have a ground overcurrent relay to operate on ground faults in either direction.

Zone 5 covers four underground lead-cable circuits between power stations 1 and 2. Each of these circuits is equipped with *HCB* pilot-wire relays, similar to the relays on lines 101 and 102 to the bar mill previously described. These relays have operated on two occasions to clear cable faults, performing satisfactorily without disturbing the rest of the system.

Zone 6 is treated as a radial feeder out of power station 2 with *IAC* phase relays. At present there are no ground relays in this section, but it is planned to install *ICC* current-polarized directional ground relays, with the direction of operation away from power station 2.

All transformer banks and 6,600-volt motors are protected with either differential relays or phase and ground relays, the ground relays being set to operate almost instantaneously in order to clear any faulty machine from the line at once.

A general over-all picture of our ground relaying scheme is shown in Figure 2. Not all lines but only the circuits controlled by the ground relays on lines are shown on this sketch. Ground relaying is particularly desirable, as the greater portion of all faults usually develop first as ground faults which may turn into phase-to-phase faults. Ground relays are also very desirable in the protection of motors and transformers, because grounding of windings to the frame is a common type of fault. By means of ground relays the machine with such a fault can be removed quickly from the line before any serious phase-to-phase fault can develop with the attendant damage due to short-circuit currents. This is an important point, as the short-circuit currents on our system are approximately 50,000 amperes while ground currents never can exceed 5,000 amperes. Because ground relays on machines are set to operate very quickly, the damage to the machine due to a ground fault in the machine is thus kept at a minimum.

Summary

The electric load in a steel plant may be compared to a public utility feeding many consumers in a congested area.

Continuity of service is guaranteed by obtaining power from more than one power supply.

Interruptions may be held to a minimum by proper phase and ground-relay protection.

Zones may be set up to isolate troubles and confine interruptions to the particular zones in which they occur.

Maintenance of Good Brush Performance

W. C. KALB
FELLOW AIEE

BRUSHES used on electric equipment have three distinct functions to perform. First, they must carry the load current into and away from the rotating element of the machine. Second, they must function as bearings on the surface of the commutator or slip ring, preferably without any applied lubrication, and at surface speeds sometimes in excess of 100 miles per hour. Third, on commutating machines, the brushes must control within safe limits the short-circuit current resulting from uncompensated voltages in the armature coils undergoing commutation and must resist the destructive action of the very high local current densities which are frequently characteristic of the commutation cycle.

This is quite an assignment. In addition to the need for good electrical conductivity, heavy demands are placed on the lubricating, thermal, and refractory properties of the brush material. The combination of these characteristics best adapted to one application obviously may not be best for another in which a different relationship of the three major brush functions is encountered. Before undertaking a discussion of the maintenance of good brush performance it is therefore advisable to consider the criteria by which acceptable performance of these essential brush functions is judged.

Criteria of Good Brush Performance

1. Sparking, the most obvious indication of unsatisfactory brush performance, may result from a variety of causes. Among the numerous causes may be mentioned poor commutator surface; faulty commutation cycle, such as completion of current reversal too early or too late; faulty machine adjustment; various mechanical or electrical faults in the machine; bad load conditions; vibration; and incorrect brush grade. Freedom from sparking of injurious intensity may well be considered the first criterion of good brush performance.

2. Operation with minimum commutator wear is another measure of satisfactory brush performance. Commutator wear accompanied by evidence of burning on the commutator surface is usually traceable to imperfect contact between brushes and commutator. This, in turn, may be due to low spring pressure, tight brush holders, excessive vibration, high or feather-edge mica, or brush chattering. A bright surface on the worn commutator indicates actual abrasion, either from foreign material in the brush face, or from the use of an abrasive brush grade.

3. The nature of the surface film on the commutator is being given increasing recognition as a gauge of brush performance. Satisfactory operation requires that a smooth surface film of uniform character be maintained. This subject will be discussed in greater detail later.

4. Brush performance is also judged on the basis of associated losses or, conversely, machine efficiency. Energy losses from short-circuit currents during commutation, from the resistance of a glazed commutator surface to the passage of load current, from the unbalancing effects of selective action, and from brush friction may at times be enough to affect seriously the efficiency or the satisfactory performance of a motor or generator. However, with proper brush selection and operation, these losses can be kept to a small value.

5. Quietness of operation is dependent, primarily, on the maintenance of uninterrupted contact between brushes and commutator. On some applications an audible tone from the brushes in operation may be sufficient reason for condemning the grade. Even where freedom from noise is not an essential feature of performance, the firm contact on which quiet operation depends has an important influence on satisfactory performance in other respects.

6. Brush life is often given undue weight in judging brush performance. While long brush life is desirable, its attainment at the sacrifice of good performance in some other respects may prove far from economical. When satisfactory brush performance in respect to the criteria previously cited is achieved, reasonable brush life may well be expected to follow as a natural result.

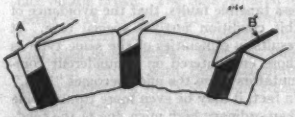

Figure 1. Undercut mica with U-shaped slots

A—Rough edges may be raised by the undercutting tool. These should be removed by beveling

B—Slotting off center leaves mica fins

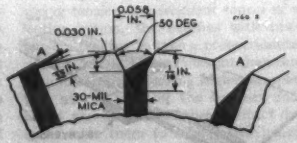

Figure 2. Undercut mica with V-shaped slots

A—Mica fins are left in V slots that are too shallow or off center

Good Commutator Surface Essential to Good Brush Performance

Economical maintenance and satisfactory operation of electric equipment is dependent to a large degree upon the care used in preparing the surface of the commutator or slip rings and the attention given thereafter to keeping the surface in good condition. Systematic inspection and immediate correction of incipient faults greatly reduce liability to shutdown, as well as the cost of repairs incurred when faults such as bar burning, high mica, and flat spots are allowed to develop to a serious stage.

Surfacing

The best way to produce a true cylindrical surface on a commutator or slip ring is by turning or grinding. Before undertaking this operation on a commutator it should be carefully examined to make sure that all segments are firmly clamped by the V rings and, if necessary, it should be retightened. On large machines the grinding or turning operation is usually performed with the armature in the machine but on small machines it is usually transferred to a lathe. In either case, rigid mounting of the turning tool or grinding equipment is essential to good results. Windings should be shielded from copper clips and dust during this operation. A diamond-shaped tool and fine-pitch feed are usually preferred for turning, finishing with a very light cut to minimize "threading." Some manufacturers use an actual diamond tool on small high-speed commutators where a high degree of precision is essential. Mounting the armature and its bearings on V blocks, rather than on lathe centers, is also recommended practice for lathe finishing. Grinding fixtures are available carrying a revolving abrasive wheel and there are also other types using a stationary stone held in a manner similar to a lathe tool.

The commutator stone is definitely superior to sandpaper for hand surfacing of commutator and rings. Such stones, of suitable grit and bond and with handles attached, are readily available. The stone should be formed or worn to the same curvature as the surface being finished and should have a span in the direction of rotation greater than the broadest flat spot to be removed. Presenting a rigid surface, the hand stone, properly applied,

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will remove high mica, flat spots, burned bar edges and other surface defects without disturbing the cylindrical contour. By the use of a hand stone when such faults first appear, the need for turning or grinding can be postponed or entirely avoided. A hand stone should also be used after turning to remove all traces of the thread-like ridges left by the lathe tool. The stone should be pressed firmly against the commutator or ring and moved very slowly from side to side to avoid diagonal scratches.

Sandpapering is an acceptable method of removing deposit from a commutator surface, correcting roughness, or reducing high mica, provided the accurate contour of the surface has not been seriously disturbed. However, sandpaper cannot be depended on to remove flat spots. Because the paper is flexible it tends to broaden, rather than remove, the flat spot. The rigid face of the commutator stone, on the other hand, will cut down the high areas and remove the spot by restoration of a true cylindrical surface. Best results with sandpaper are obtained by attaching it to a wooden block formed to the radius of the commutator or ring. Paper of relatively fine grain is usually preferable.

Undercutting

The practice of undercutting the mica of commutators has now attained such general approval that there is no need to argue its merits. There are relatively few applications on which flush mica commutators have any advantage over undercut. The tools used for undercutting range from the hacksaw blade and triangular file for hand operation to a great variety of motor-driven tools, most of which use revolving disk-shaped cutters. Shape of slot is largely a matter of individual preference. The square bottom or U-shaped slot shown in Figure 1 has the advantage of being effective until the commutator is worn down the full depth of the undercut. Accumulated dust, however, is not thrown out from the U-shaped slot as readily as it is from the V-shaped slot, Figure 2. Depth of U-shaped slots is generally made about 1/32 inch to 3/64 inch. Cutters for V-shaped slots are made with different angles between the cutting edges. Forty-degree cutters are generally preferred for thin mica, 50-degree for medium mica, and 60-degree for thick mica. The depth of cut should be sufficient to leave approximately 1/32 inch of mica-free copper at each side of the slot. Before undercutting a commutator, it should be turned, ground, or stoned depending on its previous condition, so that all surface faults, such as grooves, ridges, and flat spots, are eliminated. After undercutting, the commutator surface should be lightly polished with a fine-grain commutator stone or sandpaper to remove the small burrs raised at the edges of the slots by the undercutting tool. It is also good practice to burnish the commutator surface with hardwood blocks applied under heavy pressure. Hard maple is an excellent wood for this purpose and should be applied with the end grain against the commutator. This produces a well polished surface and, since considerable heat is developed, tends to form an oxide film on the segments which has a favorable influence on brush performance.

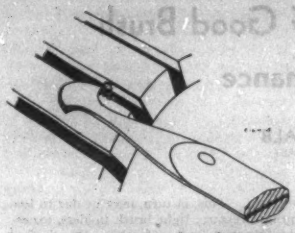

Figure 3. Removing mica fin and chamfering edge of commutator bar with home-made tool

Dimensions of slots exaggerated for clarity

Mica Fins

A frequent source of trouble on undercut commutators is variously described as "feather-edge mica," "side mica," or "mica fins." These terms refer to the thin edges of mica often left along the sides of the slots through failure to center the cutter accurately on the mica, deviation from a straight line parallel to the commutator segments, or insufficient depth of V-shaped slots. Commutator wear may also reach mica fins not in evidence immediately after undercutting. Troubles traceable to feather-edge mica are encountered with such frequency on commutating equipment, and the cause is so often overlooked in the search for less tangible faults, that the avoidance of this condition justifies special care. It results in difficulties of the same type as those encountered on nonundercut commutators when the mica becomes "high." In fact, it may be even more troublesome than ordinary high mica due to the tendency for small particles of mica to break loose and become embedded in the brush faces. Sparking, bar burning, picking up of copper by the brush faces, and noisy operation are among the operating difficulties often traced to this fault. After undercutting the commutator, or whenever faulty operation indicates the possible presence of feather-edge mica, every slot on the commutator should be inspected carefully. If mica fins are detected they should be removed with a knife blade or other suitable tool. An effective tool for this purpose can be made by grinding a hook-shaped cutting edge at the end of a hacksaw blade and attaching a suitable handle. This type of tool can be drawn through the slot, as illustrated in Figure 3, cutting at the root of the side mica on one side and slightly chamfering the opposite edge of the slot at the same time. Of course, frequent resharpening will be necessary to insure complete removal of the mica. After completing this operation the slots and armature windings should be blown out thoroughly to remove all loose particles of mica and copper.

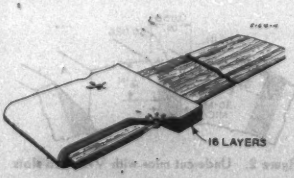

Figure 4. Canvas wiper of the type described in text

Canvas Wiper

Another home-made device which has proved effective in maintaining good brush performance is the canvas wiper, Figure 4. Several layers of six- or eight-ounce hard-woven canvas or duck are folded over the end of a strip of strong pliable wood of suitable dimensions and secured by rivets. Countersinking the strip at the points where the rivets are inserted reduces the danger of the rivet heads making contact with the commutator. The canvas is held against the commutator under heavy pressure and rubbed slowly back and forth. This removes oil, grease and smudge from the commutator surface without hazard of the hand coming in contact with live parts of the machine. Applied with sufficient frequency, it removes the oxidation at bar edges caused by sparking and may forestall the development of serious bar burning. However, it does not destroy the desirable oxide or electrographitic surface film on which good brush performance is largely dependent. Maintenance departments which have adopted the use of the canvas wiper as regular practice have found commutator maintenance greatly reduced. Frequency of application depends on the tendency for surface deposit to accumulate. With moderate accumulation, daily application is recommended while more severe conditions may require application at shorter intervals. This has proved a very effective method of establishing and maintaining a good commutator surface with a minimum of major resurfacing operations.

Installation and Setting of Brushes

Users of electric equipment seldom have any choice in regard to the type of brush holders supplied on motors and generators but are not thereby relieved of the responsibility of keeping brush holders in good condition, free from any accumu-

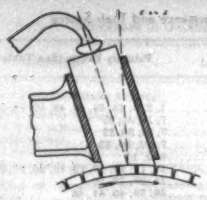

Figure 5. Brush held in trailing position

lation which might interfere with normal movement of the brushes, accurately located and firmly secured, and correctly adjusted in respect to spring pressure.

Brush Angle

The angle at which the brush is held against the commutator is a subject which might be discussed at great length. For the present, however, it is probably sufficient to make the following general recommendations. The radial position is usually preferred for reversing motors although there are numerous examples of successful operation with the brushes inclined at a substantial angle from the radial. For trailing operation, that is, with the commutator revolving toward the wider of the two angles at the brush face, as in Figure 5, an inclination of 15 degrees from the radial is representative of general practice. A certain amount of wedging action may be encountered when brushes having a relatively high coefficient of friction are operated at larger trailing angles. With leading operation, where the commutator revolves toward the acute angle at the brush face, as in Figure 6, an inclination of from 30 to 37½ degrees is preferred. This insures a reactive force against the leading side of the brush holder which gives stability to the brush position. The critical angle for leading operation is in the neighborhood of 20 degrees. At this and smaller angles, disturbances to brush friction are liable to induce chattering of the brushes. In practice it is customary to bevel the top or free end of brushes operated at a leading angle, as indicated by dotted line in Figure 6, thus giving increased stability to the brush position.

Staggering

Most brushes now used have very mild abrasive properties, or none at all, so that the need for staggering the position of the brushes around the commutator to prevent the brushes wearing deep grooves no longer exists. However, the practice is continued for the sake of uniformity in commutator-surface appearance. A rule which should be observed when setting the brush holders in staggered relation is to make this arrangement in positive and negative pairs, as shown in Figure 7. A brush of one polarity should be followed, in the same path, by one of the opposite polarity. The next pair, in a circumferential direction, should then be shifted in an axial direction from the first pair. The character of the surface film developed under the positive brushes differs from that under the negative brushes, but when the brushes are staggered in pairs as described, no part of the commutator is contacted by brushes of one polarity more than by those of the other.

Symmetry

Lack of symmetry, either electrical or mechanical, results in inequalities of voltage between different pairs of brush-holder studs and may be the source of heavy circulating currents in the armature. Overheating of armature windings and more severe sparking on some brush studs than on others are operating faults often traceable to lack of electrical or mechanical symmetry. When such indications are noted, check the spacing of the brushes from toe to toe, the alignment of brushes on each stud with the commutator segments, the spacing of field poles, the length of air gaps, and the security of cross connections. Any inequalities found should be corrected.

Sanding Faces

New brushes, when first installed, should be carefully sanded to the contour of the commutator. A coarse grade of sandpaper is suitable for removing most of the carbon, but the final surface should be formed with paper of fine grain or with a brush-seating stone. The latter is a fine-grain free-wearing stone of special composition sold by various manufacturers of commutator-maintenance equipment. Sandpaper should be drawn only toward that side of the brush holder against which the brush rests when in operation and the brush should be lifted to return the sandpaper strip for succeeding strokes. This avoids forming a double face on the brush. The time required for facing in the brushes will be reduced by using considerably heavier pressure than that used in operation. Keep the sandpaper in contact with the commutator during the cutting stroke to prevent rounding the edges of the face.

Spring Pressure

Careful attention should be given to the adjustment of spring pressure on the brushes. Many instances of faulty brush operation have been traced to improper or unequal spring tension. Unequal spring tension is a frequent source of selective action, the brushes with heavy tension tending to take a proportionately larger share of the load current than those with less. The resulting higher temperature at the faces of the brushes under heavy pressure lowers their contact drop and causes them to take a still heavier share of the load. It can readily be seen that this effect is cumulative and may result in excessive overloading of individual brushes. Pressure on all brushes on a machine should, therefore, be kept as nearly equal as the adjustment provided on the brush holders will permit. For any grade of brush and type of service there is a certain range of pressure within which best performance is obtained. At higher pressures friction losses and brush wear are increased, while at lower pressures the brushes are not kept in intimate contact with the commutator. Sparking, injury to the commutator surface, and rapid brush wear are likely to result from operating brushes at too low a pressure. One pound below the optimum range of pressure will usually result in more rapid brush wear than one pound above the optimum range. In other words, the disintegration of the brush face from electrical causes at low pressure is greater than the increased mechanical abrasion produced by pressure correspondingly higher than the normal range. That is why more brush complaints originate from low pressure than from high pressure. The relationship of brush pressure to rate of wear for a typical electrographitic grade is shown in Figure 8. Brush pressures are recommended by the manufacturer in terms of pounds per square inch. To determine this value, divide the pressure in pounds parallel to the length of the brush by its cross sectional area in square inches. As a rule no correction is made for the increased area of face resulting from a face bevel. Manufacturers' specific recommendations should be followed, but the following figures, in pounds per square inch, are indicative of representative practice.

Industrial service:

Electrographitic grades	2–3
Carbon and carbon-graphite grades	1½–2½
Soft graphite grades	1½–2
Metal-graphite grades (slip rings)	2½–3½
Fractional-horsepower motors	4–5
Traction service	5–7

Neutral Position

The fact is generally understood that brush position has a pronounced influence on commutation. On noninterpole machines the neutral position, that is, the

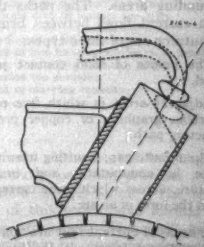

Figure 6. Brush held in leading position

position giving best commutation, shifts with the load. A permanent setting of brush position must, therefore, be a compromise between no-load and heavy-load conditions and can only be determined by a consideration of load characteristics. Interpole machines, on the other hand, have a fixed neutral point, theoretically unaffected by change in load. There is accordingly one best brush position for all load conditions. Time will not be taken for a discussion of the several methods in use for locating the neutral point on interpole machines. It should be mentioned however, that there is little latitude in neutral position on most machines of interpole design. If the brushes are shifted appreciably from the correct position a compounding effect from the interpole field flux is introduced.

Nature of Brush Contact and Commutator Surface Film

It is now widely recognized that brush performance is influenced to a pronounced degree by the interface conditions between the brush and the commutator on which it bears. A great deal of study has been and is still being given to this subject. The commutator surface and the brush face, regardless of the high polish acquired, do not present to each other surfaces of exactly identical curvature or profile. The play of the brush in its holder and the yielding of supporting members under stress may give the brush face a slightly longer radius of curvature than the commutator. The effective area of contact for a particular brush at a given instant may represent, therefore, a relatively short span of the brush face in the direction of rotation. Furthermore, within this area, actual contact between brush and commutator is limited to a few points, or very small areas, carrying the load current at an extremely high current density. Rotation of the commutator, mechanical abrasion, and the disintegrating effects of the high localized current densities cause constant shifting of these areas of contact so that contact at any given point of either brush face or commutator is probably of extremely short duration, except for firmly embedded points which protrude to a substantial degree from the surrounding areas. The paths through which current flows between brush and commutator are of three types:

1. The points of solid contact just described.

2. Adjacent areas in which free particles of carbon, graphite, or copper provide a conducting path.

3. The minute gap, resulting from the difference in commutator and brush-face curvature, across which some current may pass in the form of an arc.

These areas of current flow are constantly and rapidly shifting within the boundaries of the brush face and in a very short space of time, possibly comparable to one full revolution of the commutator, current flow will have occurred through every portion of the brush face, giving it an appearance indicating complete and uniform contact.

Table I. Indications of Unsatisfactory Performance and Their Source

Indications	Immediate Causes	Primary Faults (See Table II)
Appearing at brushes		
Sparking	Commutator surface condition	1, 2, 3, 43, 44, 45, 46, 49, 58, 59
	Overcommutation	7, 12, 31, 33
	Undercommutation	7, 12, 30, 32
	Too rapid reversal of current	7, 12, 30, 32
	Faulty machine adjustment	8, 9, 11
	Mechanical fault in machine	14, 15, 16, 17, 18, 19, 20, 21, 22
	Electrical fault in machine	25, 27, 28, 29
	Bad load condition	38, 39, 40, 41, 42
	Poorly equalized parallel operation	7, 13, 23, 34
	Vibration	50, 51
	Chattering of brushes	See "Chattering or noisy brushes"
	Wrong brush grade	54, 56, 58
Etched or burned bands on brush face	Over commutation	7, 12, 31, 33
	Undercommutation	7, 12, 30, 32
	Too rapid reversal of current	7, 12, 30, 32
Pitting of brush face	Glowing	See "Glowing at brush face"
	Embedded copper	See "Copper in brush face"
Rapid brush wear	Commutator surface condition	See specific surface fault in evidence
	Severe sparking	See "Sparking"
	Imperfect contact with commutator	11, 14, 15, 16, 50, 51
	Wrong brush grade	53, 57
Glowing at brush face	Embedded copper	See "Copper in brush face"
	Faulty machine adjustment	7, 13
	Severe load condition	38, 39, 41, 42
	Bad service condition	46, 47
	Wrong brush grade	56, 60, 61
Copper in brush face	Commutator-surface condition	2, 3
	Bad service condition	43, 46, 47, 48, 49
	Wrong brush grade	58, 60
Flashover at brushes	Machine condition	14, 35
	Bad load condition	38, 39, 41, 52
	Lack of attention	5, 11
Chattering or noisy brushes	Commutator surface condition	See specific surface fault in evidence
	Looseness in machine	16, 16, 17
	Faulty machine adjustment	10, 11
	High friction	43, 45, 49, 51, 57, 58
	Wrong brush grade	54, 57, 58
Brush chipping or breakage	Commutator surface condition	See specific surface fault in evidence
	Looseness in machine	15, 16, 17
	Vibration	51
	Chattering	See "Chattering or noisy brushes"
	Sluggish brush movement	14

Surface Film

Increased recognition is also being given to the influence of the commutator surface film on brush performance. Emphasis has been placed on the importance of this surface film by experiences encountered on military aircraft at altitudes of 25,000 feet and higher. Ordinary grades of brushes which perform in an entirely satisfactory manner at normal altitudes, wearing at a rate of one inch in several thousand hours, may wear out completely in the course of one flight at high altitude. This failure has been shown to be due to the failure of the commutator surface film under the atmospheric conditions existing thousands of feet above the earth's surface. This brings us to a consideration of the character of this surface film. It appears to be of complex structure, including in its make-up a thin layer of copper oxide on the surface of the commutator bars and a thin deposition of graphite over this oxide. On this solid layer of protective film an adsorbed layer of oxygen and water vapor is formed under normal atmospheric conditions. This adsorbed water vapor and oxygen film, although probably of submicroscopic thickness, provides boundary lubrication between the brush face and the graphite-copper-oxide film beneath. Wear of the latter film is thereby reduced and oxygen released by electrolysis of the water vapor tends to maintain the copper-oxide film. The graphite film, of course, is deposited by the brushes. At high altitude there is much less oxygen in the atmosphere and practically no water vapor, so that the boundary film disappears and the brushes come into such close contact with the commutator that atomic cohesive forces become effective. The protective graphitic and copper-oxide film is then quickly stripped off and rapid brush and commutator wear follow. A similar effect has been observed on the slip rings of rotary converters and on some commutating equipment during winter periods of extremely low humidity. Dusting and rapid brush wear has been stopped in such instances by humidifying the atmosphere of the substation or by adding some lubricating agent to the brush to take the place of the missing film of adsorbed water vapor. Such means of correction not being applicable to aircraft equipment,

Table I. Indications of Unsatisfactory Performance and Their Source (Continued)

Indications	Immediate Causes	Primary Faults (See Table II)
Appearing at commutator surface		
Rough or uneven surface		1, 2, 3, 4, 17
Dull or dirty surface		5, 44, 59
Eccentric surface		1, 10, 22, 51
High commutator bar		17
Low commutator bar	Sparking	2, 25
Streaking or threading of surface	Sparking	43, 44, 45, 46, 49, 58
	Copper or foreign material in brush face	2, 3, 46, 47, 48, 60
	Glowing	See "Glowing at brush face"
Bar etching or burning	Sparking	2, 3, 7, 12, 30, 31, 32, 33
	Flashover	5, 11, 14, 35, 38, 39, 41, 52
Bar marking at pole-pitch spacing	Sparking	25, 37
Bar marking at slot-pitch spacing	Sparking	7, 12, 30, 56, 59
Flat spot	Sparking	19, 23, 25, 41, 42, 52
	Flashover	5, 11, 14, 35, 38, 39, 41, 52
	Lack of attention	1, 5, 11
Discoloration of surface	High temperature	See "Heating—at commutator"
	Atmospheric condition	44, 46
	Wrong brush grade	59
Raw-copper surface	Embedded copper	See "Copper in brush face"
	Bad service condition	43, 45, 47, 49
	Wrong brush grade	58, 60
Rapid commutator wear with blackened surface	Burning	2, 3, 11, 14
	Severe sparking	See "Sparking"
Rapid commutator wear with bright surface	Foreign material in brush face	43, 45, 47, 49
	Wrong brush grade	60
Appearing as heating		
Heating in windings	Severe load condition	38, 41, 42, 52
	Unbalanced magnetic field	18, 19, 20, 21, 27, 28, 29
	Unbalanced armature currents	8, 19, 22, 25, 27, 28, 29, 37
	Poorly equalized parallel operation	7, 13, 23, 34
	Lack of ventilation	6
Heating at commutator	Severe load condition	38, 41, 42
	Severe sparking	7, 8, 9, 12, 20, 33, 45, 56
	High friction	10, 11, 36, 43, 45, 49, 57, 58
	Poor commutator surface	See specific surface fault in evidence
	Depreciation	24
	High contact resistance	55
Heating at brushes	Severe load condition	38, 41, 42
	Faulty machine adjustment	7, 10, 11, 12, 26
	Severe sparking	See "Sparking"
	Raw streaks on commutator surface	See "Streaking or threading of surface"
	Embedded copper	See "Copper in brush face"
	Wrong brush grade	56, 57, 58, 60, 61

Table II. Primary Sources of Unsatisfactory Brush Performance

Preparation and care of machine

1. Poor preparation of commutator surface.
2. High mica.
3. Feather-edge mica.
4. Bar edges not chamfered after undercutting.
5. Need for periodic cleaning.
6. Clogged ventilating ducts.

Machine adjustment

7. Brushes in wrong position.
8. Unequal brush spacing.
9. Poor alignment of brush holders.
10. Incorrect brush angle.
11. Incorrect spring tension.
12. Interpoles improperly adjusted.
13. Series field improperly adjusted.

Mechanical fault in machine

14. Brushes tight in holders.
15. Brushes too loose in holders.
16. Brush holders loose at mounting.
17. Commutator loose.
18. Loose pole pieces or pole-face shoes.
19. Loose or worn bearings.
20. Unequal air gaps.
21. Unequal pole spacing.
22. Dynamic unbalance.
23. Variable angular velocity.
24. Commutator too small.

Electrical fault in machine

25. Open or high-resistance connection at commutator.
26. Poor connection at shunt terminal.
27. Short circuit in field or armature winding.
28. Ground in field or armature winding.
29. Reversed polarity on main pole or interpole.

Machine design

30. Commutating zone too narrow.
31. Commutating zone too wide.
32. Brushes too thin.
33. Brushes too thick
34. Magnetic saturation of interpoles.
35. High bar-to-bar voltage.
36. High ratio of brush contact to commutator surface area.
37. Insufficient cross connection of armature coils.

Load or service condition

38. Overload.
39. Rapid change of load.
40. Reversing operation of noninterpole machine.
41. Plugging.
42. Dynamic braking.
43. Low average current density in brushes.
44. Contaminated atmosphere.
45. "Contact poisons."
46. Oil on commutator or oil mist in air.
47. Abrasive dust in air.
48. Humidity too high.
49. Humidity too low.

Disturbing external condition

50. Loose or unstable foundation.
51. External source of vibration.
52. External short circuit or very heavy load surge.

Wrong brush grade

53. "Commutation factor" too high.
54. "Commutation factor" too low.
55. Contact drop of brushes too high.
56. Contact drop of brushes too low.
57. Coefficient of friction too high.
58. Lack of film forming properties in brush.
59. Lack of polishing action in brush.
60. Brushes too abrasive.
61. Lack of carrying capacity.

special grades of brushes have been developed containing an ingredient which produces and maintains a protective film on the commutator or ring surface under the adverse atmospheric conditions of extreme altitudes. It is too early to say to what extent these or similar grades will find application under normal altitude conditions, but investigations are being conducted along this line on various types of power, traction, and industrial equipment.

The thin layer of copper oxide normally developed on the commutator surface is very beneficial to brush performance, aiding commutation and reducing brush friction. Certain forms of atmospheric contamination, particularly those of a reducing character, tend to destroy the oxide film and interfere with good operation. These contaminants injurious to the commutator surface have been termed "contact poisons." Some of the most active materials of this type are carbon tetrachloride, alcohol, acetone, turpentine, chlorine, smoke, acid, and other corrosive fumes.

Electrographitic Surface Film

Electrographitic brushes possess, to greater or less degree, the property of depositing an electrographitic surface film on the commutator which is a highly effective aid to good brush performance. It not only has its own inherent value in reducing friction and maintaining intimacy of contact between brushes and commutator, but it also provides protection to the underlying layer of oxide on the commutator surface which apparently is a factor in the maintenance of normal contact drop and commutation. To some extent this deposition occurs through the graphite of the brush being rubbed into the minute crevices of the commutator surface. There is evidence, however, that a substantial portion of this deposition results from electrolytic action and is influenced both by the characteristics of the brush and by the current density in the brush faces. A series of brush grades commercially available provides a good illustration of this point. The regular grades of this series have normal film-forming properties. They will develop and maintain a good electrographitic surface film under average load conditions on heavy-duty power equipment.

However, on applications where the average load is under 40 amperes per square inch, film may not be deposited as rapidly as it is being worn away. Spots and streaks of raw copper sometimes appear on the commutator surface, often followed by the deposition of copper particles in the brush faces and serious threading or grooving of the commutator. The rate of film deposition is doubtless a function of the combined load and short-circuit currents at the brush face since it has been observed that a machine on which the brushes are slightly off neutral may maintain a good electrographitic surface film at a lower load-current density than a similar machine in perfect adjustment. In general, 40 amperes per square inch may be considered the minimum safe current density for the regular grades of this series. The foregoing figure assumes a clean atmosphere, free from oil vapor or contaminating gases which tend to produce a film or deposit on the commutator surface. In the presence of such contamination these grades may be able to maintain the surface film at an average current density as low as 30 amperes per square inch.

A corresponding series of grades with increased film forming properties has been developed for applications where the average load current density is consistently under 40 amperes per square inch. These brushes will maintain a good surface film at current densities as low as 30 amperes in a clean atmosphere or 20 amperes where oil vapor or other atmospheric contamination tends to accelerate film formation.

In the presence of some types of contaminating atmosphere or excessive oil vapor, a surface film of such high resistance may develop that brush performance is impaired rather than improved. For such conditions there is a third group of grades which have a mild polishing action. These grades tend to remove excess film deposition and have also proved advantageous in overcoming a moderate tendency toward edge burning or marking of the commutator bars from over oxidation, such as that produced by very high current peaks in the commutation cycle. The minimum safe current density for grades of this class is usually about 50 amperes per square inch under clean atmospheric conditions or 40 amperes in the presence of a contaminated atmosphere.

Intimacy of Contact

The trend of design toward higher angular velocities and higher surface speeds for commutators and slip rings has given prominence to the importance of intimate contact being maintained between the brush and the moving surface. Interruption of contact resulting from very slight irregularities of the commutator or ring surface may be sufficient to cause sparking and injury to the surface.

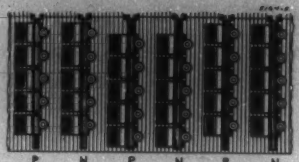

Figure 7. Correct method of staggering brushes

P—Positive *N*—Negative

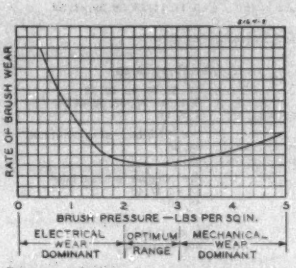

Figure 8. Relationship between brush pressure and rate of brush wear for typical electrographitic grade

Such a condition tends to become cumulative and may interfere seriously with machine performance. The nature of the surface film on a commutator, atmospheric conditions, frictional properties of the brushes, brush pressure, and angle of inclination all have an influence on the intimacy of contact at the brush face. Another factor, possibly more important than any of the foregoing, is related to the elastic property of the brush. This property is subject to accurate quantitative determination and, because of its direct influence on commutating performance, has been termed the "commutation factor." The commutation factor is an index of the capacity of the brush to absorb the shocks resulting from slight irregularities on the revolving surface. Experience with applications under widely varied conditions of service has demonstrated the importance of this property in respect to brush operation. By selecting a brush of suitable commutation factor, intimate contact between brushes and commutator can be maintained, with good commutation and quiet operation, in the face of disturbing conditions that could not readily be overcome in any other manner.

Correction of Unsatisfactory Performance

Maintenance of good brush performance is facilitated by seeking the primary source of trouble as soon as the first indication of unsatisfactory operation is observed. Immediate correction of the primary fault will avoid interruption of service and the necessity for more expensive repairs at a later date. There are numerous indications of unsatisfactory performance and a great many primary faults from which they may result. Most of these primary sources of poor performance can be grouped under the following headings:

1. Poor preparation and care of the machine.
2. Faulty machine adjustment.
3. Mechanical fault in machine.
4. Electrical fault in machine.
5. Machine design.
6. Load or service conditions.
7. Disturbing external conditions.
8. Wrong brush grade.

The problem of determining the primary source of trouble in a specific case can be simplified to some extent by a systematic analysis of symptoms. A plan for making such an analysis, together with lists of the more common indications of unsatisfactory performance and the primary faults from which they may result, is given in the appendix to this paper.

Summary

It is difficult to say what is the most important characteristic of a carbon brush. The property which makes a brush grade the ideal selection for one application may be of secondary importance on another. For heavy duty service it seems preferable that those characteristics which aid or permit the maintenance of a uniform surface film on the commutator should be given first consideration. Particular attention should be given to the ability of the brush to maintain close contact with the commutator or ring surface. In addition to care in the selection of brush grade, equal attention should be given to the initial preparation of the commutator or ring surface, avoidance of high or feather-edge mica, accurate machine adjustment, careful brush installation, maintenance of correct and uniform spring pressure, and periodic use of the canvas wiper. Such routine care costs little but aids greatly in maintaining good brush performance at minimum expense. Finally, at the first indication of unsatisfactory performance, an effort should be made to determine the primary fault and to correct it in time to prevent serious disturbance of operation.

Appendix

The accompanying tables have been prepared as a guide to systematic analysis of unsatisfactory brush performance with a view to determining the primary fault.

Phase-Comparison Carrier-Current Relaying

A. J. McCONNELL ASSOCIATE AIEE T. A. CRAMER ASSOCIATE AIEE H. T. SEELEY ASSOCIATE AIEE

DIFFERENTIAL PROTECTION is recognized as the ideal means of quickly isolating faulty electric equipment. The carrier-current relaying system described herein is a differential system comparing the phase angles, via a carrier-current channel, of the currents entering and leaving a transmission-line section, and is known as phase-comparison carrier-current relaying.

Functional Summary of Relay System

The equipment operates when fault currents are above predetermined limits, and simultaneously energizes the trip coils of the circuit breakers at both ends of a faulty line section when the fault-current magnitudes are large enough at both terminals. On all unbalanced faults, that is, other than three-phase faults, the sensitivity is such that operation is obtained with fault currents of less than full-load magnitude. For three-phase faults, the current magnitude for operation must be greater than full load. Since the system operates in response to current alone, no potential supply is necessary.

On all unbalanced faults, the carrier-current blocking signal is sent automatically, that is, independently of the operation of the contacts of any mechanical relay.

The relay operating time is, on the average, less than 2.5 cycles, and sensitivity is obtained with unusually low burden.

Only one carrier-current frequency is required and the channel is available, except during faults, for other uses such as telemetering and supervisory control. The equipment can be used on a two-frequency duplex channel if other services make such an arrangement desirable.

Carrier-Current Channel Requirement

The ideal relaying system should require only one carrier frequency in order to conserve channel space. This eliminates any system requiring simultaneous transmission from the two terminals. Comparison of more than one quantity requires either tone modulation for each quantity or a separate carrier frequency for each quantity, either of which exceeds the single-channel goal. Consequently, a single quantity is derived from the phase currents and this single quantity is used in such a way that transmission in both directions over one carrier-current channel is possible.

The means of accomplishing two-way transmission over a single carrier-current channel and the method of obtaining a single quantity for comparison are discussed hereinafter.

Fundamental Operating Principle

Fundamentally, the operating principle of this equipment is exactly the same as the first carrier-current relaying system,[1] but in the present application, the use of modern methods has eliminated the limitations of certain components of the earlier equipment. Since the fundamental principle has been explained before,[1,2] it should suffice here to review the explanation only briefly.

At each line terminal, the local single quantity derived from the polyphase currents has two functions, namely:

1. During one half cycle it causes a blocking signal to be transmitted, via the carrier-current channel, to the remote line terminal.

2. During the alternate half cycle, it causes tripping if no blocking signal is received from the remote terminal.

Since blocking requires that a signal must be received from the remote terminal in the half cycle assigned to tripping at the local terminal, the two terminals must alternate in transmitting blocking impulses during successive half cycles. The current transformers are connected so that this action occurs on external faults.

During internal faults, there is a relative current reversal of approximately 180 degrees and the two line terminals transmit blocking signals during one half cycle, leaving both terminals free to trip during the other half cycle. Since lack of a signal from the remote terminal permits tripping, tripping at one terminal (but not at both terminals) is obtained for an internal fault fed from that end only.

Derivation of Single Quantity for Comparison

In order to determine the best method of combining the three individual phase currents into a single quantity for comparison, it is helpful to examine the currents present during each type of fault in terms of symmetrical components as follows:

Single-phase-to-ground fault	I_1	I_1	I_0
Two-phase-to-ground fault	I_1	I_1	I_0
Phase-to-phase fault	I_1	I_2	
Three-phase fault	I_1		
Normal load current (no fault)	I_1		

Positive-Phase-Sequence Current

Since positive-phase-sequence current (I_1) is present during all types of faults, it immediately appears to be the logical choice for the single quantity for comparison. However, except during three-phase faults, the use of I_1 has serious objections. These are the following:

1. While I_1 is present on all types of faults, it is also present during normal load conditions. Thus, a fault can be recognized only if the magnitude of I_1 is greater than full-load current. For different types of faults at the same location, the magnitude of I_1 varies, being a maximum on three-phase faults and a minimum on single-phase-to-ground faults. Hence, if the three-phase short-circuit current is just sufficient for pickup, operation would not be obtained on any unbalanced fault. As an example, on a phase-to-phase fault, I_1 is approximately one half of its value during a three-phase fault at the same location (Appendix I).

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In Table I are listed some of the more common indications of unsatisfactory performance together with the immediate cause and primary faults from which these conditions most frequently arise. The primary faults are indicated in Table I by numbers which refer to corresponding items in Table II.

There may be several primary faults from which the same indication of unsatisfactory performance can result. This is one reason it is often very difficult to determine the exact cause of poor brush operation. On the other hand, there is usually more than one indication of a faulty condition. If the primary faults usually responsible for each of these indications are noted, and those selected which are common to all observed indications, the number of probable sources of trouble will be considerably reduced and isolation of the existing fault thereby simplified.

It is not practicable to include in these tables all indications of unsatisfactory brush performance nor all primary sources of trouble. These lists are representative of the difficulties more commonly encountered and, supplemented by other items from the experience of the observer, offer a systematic plan for diagnosing faulty brush performance and determining what corrective measures should be applied.

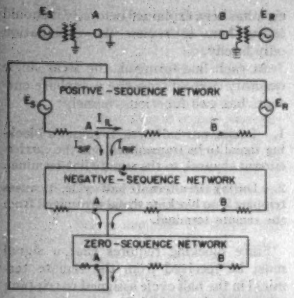

Figure 1. Symmetrical-component currents during a single-phase-to-ground fault

This means that three-phase fault current must be twice the pickup value in order to obtain sufficient I_1 for operation on a phase-to-phase fault.

2. The I_1 component is influenced by load conditions for all types of internal faults except three-phase faults. This is illustrated in Figure 1 for an internal single-phase-to-ground fault and in Appendix I, equations 7 and 8, for a phase-to-phase fault. In the positive-phase-sequence network, there are two components of each line-terminal current, a fault component which enters the faulted line at each terminal, and a through-current component. The through-current component may adversely affect the relaying system in two ways:

1. Decrease the I_1 sensitivity.
2. Cause incorrect blocking.

To summarize, the use of I_1, necessarily operating only above the maximum load value, does not provide the desired sensitivity for faults involving only one or two phases.

Negative-Phase-Sequence Current

Since negative-phase-sequence current (I_2) is present during all except three-phase faults, its use should be considered; two of its advantages being the following:

1. Under balanced load conditions there is no I_2 component, and on most transmission lines the load normally will be practically balanced.

2. The I_2 component under fault conditions is substantially unaffected by load conditions (Figure 1 and Appendix I, equations 9 and 10).

These advantages show that the use of I_2 would permit attainment of the desired sensitivity on phase-to-phase faults, and perhaps on ground faults as well, without interference from load current.

Zero-Phase-Sequence Current

The presence of zero-phase-sequence current is, of course, the best evidence of a ground fault. For ground faults, I_0 has the same advantages as I_2, that is, the desired sensitivity can be obtained without interference from load current.

Phase-Sequence Currents Used in This Equipment

Since the use of negative-phase-sequence current appears desirable for all types of faults except the three-phase fault, this equipment uses a negative-phase-sequence network with provision for developing a network output on three-phase faults. This provision consists of three phase-overcurrent relays, operation of all three shifting the network so as to introduce a positive-phase-sequence component into the network output. Thus, the equipment functions on three-phase faults at a current magnitude above full load, but for unbalanced faults, phase currents of less than full-load magnitude will cause operation.

Any relaying system for the general application must provide high sensitivity during ground-fault conditions. Because of possible unbalanced load, it is not considered practical to attempt to attain the necessary high sensitivity by means of the use of negative-phase-sequence current alone. For that reason, it is possible to use zero-phase-sequence current should the available minimum negative-phase-sequence current be too low to assure relay operation. Since the phase-to-phase fault still requires the use of negative-phase-sequence current, a combination of negative-phase-sequence and zero-phase-sequence currents is then used for unbalanced faults, the network output being of the form $(I_2 + KI_0)$.

When two different phase-sequence components are added without taking account of their relative magnitudes, it may be possible to obtain an internal ground-fault condition wherein one of the phase-sequence quantities has control at one terminal with the other phase-sequence quantity having control at the other terminal. Such a condition might easily result in a "blind spot" (failure to trip at any terminal).

Therefore, when zero-phase-sequence current is used, it is essential that the zero-phase-sequence current outweigh (by adjustment of K) the negative-phase-sequence current at both terminals under all internal-ground-fault conditions. The determination of the value of K should be as simple as possible, and here again there is a further advantage in the use of negative-phase-sequence current. Since the flow of negative-phase-sequence current is practically independent of load current,

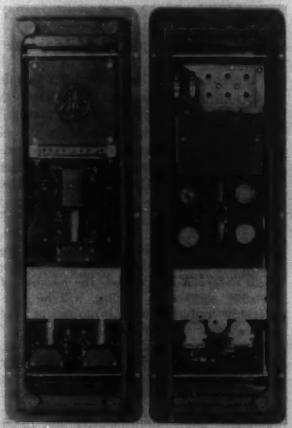

Figure 2. Network unit (left) and tripping unit (right) in draw-out cases for semiflush mounting

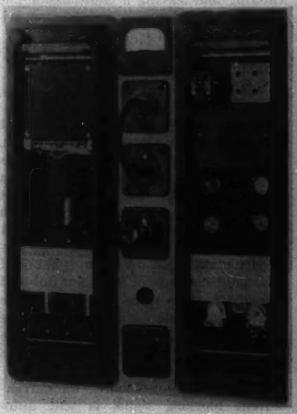

Figure 3. Network and tripping units mounted with a-c and d-c test equipment on a panel section

the determination that the system is free of blind spots is relatively simple. This is discussed more fully in Appendix VII.

Description of Relaying Equipment

The physical embodiment of the operating principles developed and outlined in the foregoing is shown in Figure 2 which illustrates all the relay elements mounted in drawout cases for convenience in adjustment and maintenance. Figure 3 shows these cases assembled with test equipment on a panel. The relations of the various elements are shown in the block diagram, Figure 4, and Figure 5 is a simplified elementary diagram of the circuit.

All of the tubes are type 25*B6G* like those used in the associated carrier-current transmitter-receiver. All of the auxiliary relays except the seal-in relay are of the telephone type, operating at their normal contact pressures, thus insuring reliability proved by long experience.

Phase-Sequence Network

With reference to Figures 2 and 5, the network is housed in the left-hand case, and consists of transformers $T1$ and $T2$, resistors $R1$, $R2$, and $R3$, and capacitor $C1$. $T1$ and $T2$ are fed from phases a and c, respectively, and $R3$ and $C1$ provide a 60-degree phase shift of the output of $T1$ so that, with balanced load, the voltage across $C1$ is in phase with the output of $T2$, which is then adjusted to equal magnitude by $R2$ so that the vector difference is zero. Zero-phase-sequence current is neutralized by ground-current windings, one of which has taps for adjustment of K. Equation 18, Appendix II, shows that the output of such a network is proportional to negative-sequence and zero-sequence currents only, and independent of positive-sequence current. On a phase-to-phase fault, such a network gives the same magnitude of output voltage regardless of which pair of phases is involved.

In order to provide for a three-phase fault, overcurrent relays in the three phases (O, Figure 5) are so connected that if all three pick up, they change the setting of $R1$ so as to unbalance the network and thus introduce a positive-sequence component into the output (equation 18a, Appendix II).

Amplifier

The amplifier allows the use of a low-burden network by permitting it to operate into a high impedance, and provides energy to drive the carrier-current transmitter as explained later. Also, the amplifier output controls the fault detector and provides the comparer with a local voltage for comparison with the incoming carrier-current signal. These elements are described in the following sections.

The amplifier consists of two tubes operating in push-pull through an output transformer which provides a match with the load resistance consisting principally of the transmitter screen grids.

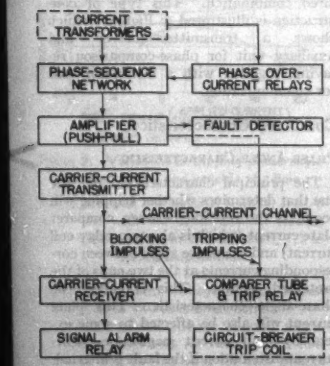

Figure 4. Block diagram showing relations between elements of the protective system

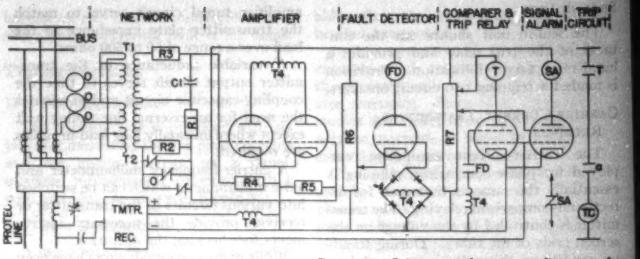

Figure 5. Schematic elementary diagram of the protective system

C—Capacitor
FD—Fault detector
O—Phase overcurrent relay
R—Resistor
REC.—Carrier-current receiver
SA—Signal-alarm relay
T—Trip relay
TC—Circuit-breaker trip coil
T1, T2, T4—Transformers
TMTR.—Carrier-current transmitter

Fault Detector

The fault detector is controlled by the amplifier, rather than by the network output directly, in order to take advantage of its voltage amplification.

This element is necessary to insure (on an external fault) that the network output is sufficient to drive the transmitter and produce an adequate blocking signal at the remote terminal, before permitting any attempt to trip. If the same carrier channel is used for communication, the fault detector also serves to transfer control of the channel temporarily from communication to relaying for the duration of a fault.

The fault detector, Figure 5, consists of a voltage-divider resistor, a full-wave rectifier, a tube, and an auxiliary relay for its plate circuit. The rectifier is supplied from a separate winding on the amplifier output transformer. The use of a fault-detector tube permits compensation, by proper biasing, for the reduction of amplifier output voltage with d-c supply voltage, thus providing a fault-detector pickup which is substantially constant over an adequate range of d-c supply voltage.

Comparer and Trip Relay

All of the elements described in the foregoing, together with the carrier-current transmitter and receiver, are subsidiary to the comparer. They gather and deliver to the comparer the information necessary to determine the fault location. The comparer makes the decision in accordance with the previous discussion under "Fundamental Operating Principle."

The comparer consists of a tube, a voltage-divider resistor to adjust its plate voltage, and the trip relay in its plate circuit. The tube is mounted on the relay auxiliary unit in the carrier cabinet to minimize the pickup in the lead from the carrier receiver to the comparer control grid. The other elements are mounted in the tripping relay case, Figure 2.

A winding of the amplifier output transformer $T4$, Figure 5, energizes the screen grid of the comparer tube, positive relative to the cathode, during one half cycle, and negative during the other half cycle. During the positive half cycle, the comparer tube will conduct and cause the trip relay to operate if no incoming carrier-current signal is received during that half cycle. On the other hand, reception of a carrier-current signal during that half cycle causes a negative voltage (rectified carrier signal) to be applied to the control grid, thereby blocking tube conduction, and consequently, operation of the trip relay. Figure 6 shows oscillograms of the carrier-frequency voltage during internal and external faults, and the d-c blocking impulses on the comparer control grid during an external fault.

Signal Alarm

The signal alarm provides a means for calling a person to the carrier telephone (simplex) and for indicating the failure of the d-c supply or opening of the heater of any tube (since all five heaters are in series).

This element consists of a tube, a voltage-divider resistor to adjust its screen-grid voltage, and an auxiliary relay in the plate circuit. The tube is mounted in the carrier cabinet with the comparer tube to minimize pickup, the other elements being mounted in the tripping relay case, Figure 2.

The screen-grid voltage is adjusted so that the signal-alarm tube normally carries enough current to pick up the signal-alarm relay. When carrier current is received, the same negative voltage that served as blocking voltage in the comparer is applied to the control grid, reducing the signal-alarm plate current, thereby causing the auxiliary relay to drop out and close the external alarm circuit.

Seal-in Unit

The seal-in unit shunts out the contacts of the trip relay and provides a hand-reset target indication. Provision is made for tripping two circuit breakers.

Carrier-Current Transmitter-Receiver

The carrier-current equipment employed for phase-comparison relaying is essentially the same as that used for directional-comparison relaying. The transmitter is controlled by the voltage on the screen grids of the tubes. During stand-by conditions, this voltage is zero and no carrier is transmitted.

When the 60-cycle excitation voltage from the network amplifier is applied to the screen-grid circuit, the transmitter sends a signal on the positive half cycle and is definitely blocked during the negative half cycle of the excitation wave. The transmitter cannot lock in and transmit continuously.

The carrier-current receiver rectifies and filters the incoming carrier wave and thus provides a pulsating d-c blocking voltage which is applied to the control grid of the comparer tube. A twin-diode tube is used in the receiver; one of the diodes is used for the relaying function while the other is used to drive an audio amplifier for telephone or other services employing audio modulation. These diodes operate on opposite half waves of the carrier-frequency cycle to obtain a balanced load on the receiver circuit and to reduce interaction between the two circuits.

The transmitter consists of a single-tube master oscillator driving a four-tube power amplifier. The operating frequency range is 50 to 150 kilocycles, and the temperature stability is better than 0.005 per cent per degree centigrade. Variable permeability tuning is used in all tuned circuits. Taps on the power-amplifier tuned circuit serve to match the transmitter plate impedance to the load over a range of 50 to 500 ohms.

A variable inductance in the transmitter output circuit serves to tune the coupling-capacitor circuit and eliminates the need for an external line-tuning unit except where unusually long lead-in cables are required.

A carrier-frequency milliammeter and a d-c milliammeter which can be switched into various circuits in the transmitter or receiver provide the necessary instruments for checking the operation.

While many carrier relay sets have been installed outdoors, the present trend is for indoor installation. The connection between the carrier set and the coupling capacitor is made with low-loss concentric cable which may be run in ordinary conduits or ducts, or buried in the ground.

Other Functions

Like other carrier relaying installations where the carrier is controlled by a fault detector, the carrier channel is available for other functions such as telephone, remote control, telemeter readings, and supervisory control. The operation of the fault detector cuts off the auxiliary services and gives the relaying function full use of the carrier channel during a fault.

Construction

The carrier-current equipment is built on chassis units having standardized unit dimensions. Many standard units, such as audio oscillators, modulators, and receivers, are available to make up any desired combination. This type of construction is illustrated in Figure 7 which shows a transmitter–receiver and auxiliary unit for phase-comparison relaying, together with a modulator unit for communication.

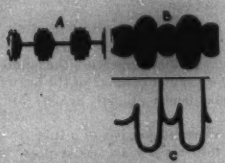

Figure 6. Oscillograms of voltages

A—At terminals of carrier-current set during internal fault. Ripples are due to heterodyne between simultaneous signals of local and remote transmitters. (Length of trace—three cycles at 60 cycles per second)
B—At terminals of carrier-current set, during external fault. Large amplitude is local signal; small amplitude, remote signal
C—At control grid of comparer tube, during external fault, 2.5 × pickup current. This pulsating d-c blocking signal results from rectification of the carrier-frequency voltage of B. Zero axis added at top

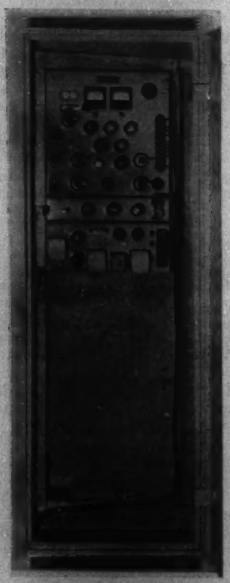

Figure 7. Carrier-current equipment for phase-comparison relaying

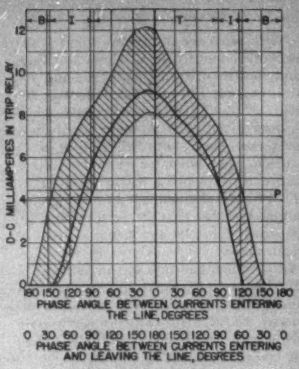

Figure 8. Phase-angle characteristic of one of a pair of production units

Heavy line is for:
1.5 × pickup current
ten-decibel line loss
129 volts direct current at each station
Shaded band covers the range from
1.5 × pickup current in each terminal
five-decibel line loss
110 volts direct current
to
20 × pickup current in each terminal
15-decibel line loss
140 volts direct current

B—Blocking zone
I—Indeterminate zone, where tripping depends on the afore-mentioned variables
P—Range of pickup of tripping relay
T—Tripping zone
(On external faults, the through current is at the same phase angle so that only a narrow band is required for blocking)

Combined Characteristics

Phase-Angle Characteristic

The principal characteristic, and the one that determines whether tripping will occur, is the relation between comparer plate current (which is also trip-relay coil current) and the phase angle between corresponding currents at the two ends of the protected section. This is called the phase-angle characteristic. This plate current will also be affected to some extent by fault-current magnitude, fault-current distribution if the fault is internal, carrier-frequency line losses, d-c source voltage at the local terminal, and d-c

source voltage at the remote terminal.

This phase-angle characteristic indicates the margin available for blocking on an external fault, and for tripping on an internal fault. Since no single value of fault current or line losses can be considered as normal, the choice of standard conditions is arbitrary; these have been chosen as 1.5 times fault-detector pickup, ten-decibel line loss, and 129 volts, direct current. The solid line of Figure 8 is typical of the average comparer plate (trip relay) current of one unit as a function of phase displacement between the two terminals. This curve is for normal conditions of control voltage, line loss, and fault-current magnitude. The shaded area shows the cumulative effect, on that characteristic, of the most adverse combination of all variables.

Figure 9 shows separately the effects of each variable on the phase angle at which tripping occurs, with all the other variables at standard value.

Fault-Detector Pickup

Figure 10 shows the dependence of fault-detector pickup and drop-out on d-c source voltage.

Operating Time

Figure 11 shows the dependence of operating time on current magnitude. These are typical values, not necessarily maximum for any unit.

Burden

The maximum burden on any one current transformer for any fault not involving ground is 0.2 ohm. The maximum burden on any current transformer for a single-phase-to-ground fault is 1.1 ohms.

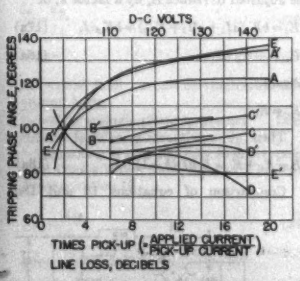

Figure 9. Variations in tripping phase angle due to changing one variable at a time

A to *E* are with one terminal leading, and *A'* to *E'* are with the other terminal leading

A, *A'*—Equal current in both terminals, 1.1 to 20×pickup current

B, *B'*—Line loss, 5 to 15 decibels

C, *C'*—D-c control voltage at local station 110 to 140 volts direct current

D, *D'*—D-c control voltage at local station dropped to 100 volts for two seconds after being at 110 to 140 volts for two minutes

E, *E'*—Current at local station 1.5×pickup, current at remote station 1.1 to 20×pickup

Testing Facilities

D-C Test Equipment

The tripping unit is provided with six jacks for measuring the five plate currents and the heater current, on a panel-mounted milliammeter provided with a cord and plug, as shown in Figure 3.

A-C Test Equipment

A five-position switch (shown in Figure 3) and an artificial-load resistor are provided to cut the relays out of service and make an over-all check of both pairs of relays and the carrier apparatus. If the switches are turned in like directions, the test currents applied to the relays simulate an internal fault, and the tripping impulse which should result lights a lamp but is blocked from the trip coil by a switch contact. If the switches are turned in opposite directions, the test currents simulate an external fault, and failure to again light the indicating lamp proves successful blocking. The test current is purposely chosen about ten per cent above the pickup value, and failure to trip or to block at this current indicates that maintenance is required.

Application

Since the equipment described here is based upon current magnitude, it is essential that currents in excess of the relay pickup (with a margin) be available. If simultaneous operation is required, pickup current must be present at each terminal upon the inception of the fault. On the other hand, sequential tripping can be obtained with initial current below pickup at one terminal, if the redistribution of current, upon the operation of the first circuit breaker, is such as to provide pickup current for operation of the second relay.

The amount of margin of calculated fault current above pickup is a matter of personal opinion. However, it is believed that a margin of 50 per cent above pickup is acceptable. This margin can reasonably be reduced at one terminal if a margin of 50 per cent above pickup is available after the other terminal circuit breaker has opened.

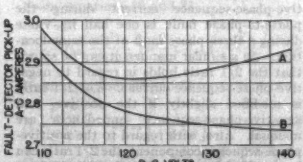

Figure 10. Fault-detector pickup

A—At 110 to 140 volts direct current

B—After operating at 100 volts for two seconds preceded by operation at 110 to 140 volts

It is conservative to assume that the currents which actuate the relay will be those corresponding to transient generator reactance. Since most short-circuit studies are based upon subtransient reactance, currents so based should be decreased by an estimated factor.

The application of any relaying system usually passes through two distinct phases. First, it is necessary to determine, with minimum effort, that a particular system is applicable in a given situation. Later, the application is studied in greater detail to determine the actual settings, operating margins, and other items.

Regarding the relaying system described herein, the first phase, the determination of its applicability, is discussed in the following section. The second phase is outlined in Appendix VII.

Three-Phase Faults

In order for the equipment to trip for an internal three-phase fault, the secondary current must be above the three-phase pickup of the relay, eight amperes.

Ground Faults (Using Negative-Phase-Sequence Current Only)

For ground-fault operation, sufficient negative-phase-sequence current will be available if the total current in the fault is approximately the same for three-phase and single-phase-to-ground faults. More precisely, negative-phase-sequence current alone may be used if the ratio of the *total* three-phase fault current to the *total* single-phase-to-ground fault current ($I_{3\phi}'/I_{G}'$) is between 0.8 and 1.5 for an internal fault at either terminal (Appendix IV).

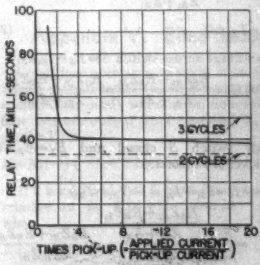

Figure 11. Operating time

Ground Faults (Using Zero-Phase-Sequence Current)

If the ratio ($I_{3\phi}'/I_{G}'$) is outside of the limits 0.8–1.5, it may be necessary to add ground-current excitation. For zero-phase-sequence excitation to predomi-

nate, one of the following conditions must be met:

If (I_{sb}'/I_0') is less than 1, then C_1/C_0 must be less than 8.5 (equation 45, Appendix V). If (I_{sb}'/I_0') is greater than 1, then

$$\frac{C_1}{C_0}\left[3\frac{(I_{sb}')}{(I_0')}-2\right]$$

must be less than 8.5 (equation 46, Appendix V), where

$C_1 = I_{sb}/I_{sb}'$
$C_0 = I_0/I_0'$
I_{sb} = portion of I_{sb}' at terminal in question
I_0 = portion of I_0' at terminal in question

In order for the equipment to trip for internal ground faults when ground-current excitation is used, the secondary ground current must be above the following:

Single-end feed—0.5 ampere*
Double-end feed—1.65 amperes (maximum)*

Appendix I. Effect of Load Current

To determine the effect of load current on positive-phase-sequence and negative-phase-sequence currents during a phase-to-phase fault and to determine the relative magnitudes of those currents during three-phase and phase-to-phase faults, refer to Figure 12 and assume that the positive-phase-sequence and negative-phase-sequence impedances are equal.**

Before fault (before closing switch S)

$$I_{S1} = -I_{R1} = \frac{E_S - E_R}{Z_{S1}+Z_{R1}} \tag{1}$$

$$I_{S2} = I_{R2} = 0 \tag{2}$$

$$E = \text{voltage across switch } S = E_S - I_{S1}Z_{S1} = E_S - \frac{E_S Z_{S1} - E_R Z_{S1}}{Z_{S1}+Z_{R1}} = \frac{E_S Z_{R1} + E_R Z_{S1}}{Z_{S1}+Z_{R1}} \tag{3}$$

With switch S closed and $E_S = E_R = 0$ (Thévenin's theorem)

$$I_1 = -I_2 = I_{S1} + I_{R1} = -(I_{S1}+I_{R2}) = -\frac{\frac{E_S Z_{R1}+E_R Z_{S1}}{Z_{S1}+Z_{R1}}}{\frac{Z_{S1}Z_{R1}}{Z_{S1}+Z_{R1}}} = -\frac{E_S Z_{R1}+E_R Z_{S1}}{Z_{S1}Z_{R1}} = -\frac{E_S}{2Z_{S1}} + \frac{E_R}{2Z_{R1}} \tag{4}$$

$$I_{S1} = -I_{S2} = \left(\frac{E_S}{2Z_{S1}} + \frac{E_R}{2Z_{R1}}\right)\frac{Z_{R1}}{Z_{S1}+Z_{R1}} = \frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{S1}(Z_{S1}+Z_{R1})} \tag{5}$$

* On two-phase-to-ground faults, ground current may be calculated by means of equation 36, Appendix III.

** Negative-phase-sequence machine reactance is nearly equal to transient and subtransient reactance and hence is nearly equal to positive-phase-sequence reactance during the first few cycles after a fault.

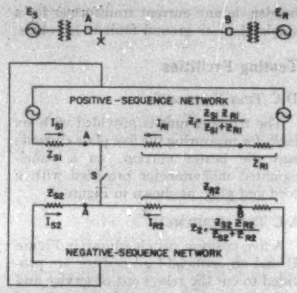

Figure 12. Symmetrical-component currents during a phase-to-phase fault (for Appendix I)

$$I_{R1} = -I_{R2} = \left(\frac{E_S}{2Z_{S1}} + \frac{E_R}{2Z_{R1}}\right)\frac{Z_{S1}}{Z_{S1}+Z_{R1}} = \frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{R1}(Z_{S1}+Z_{R1})} \tag{6}$$

Total Current

From equations 1 and 5

$$I_{S1} = \frac{E_S - E_R}{Z_{S1}+Z_{R1}} + \frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{S1}(Z_{S1}+Z_{R1})} \tag{7}$$

From equations 1 and 6

$$I_{R1} = -\frac{E_S - E_R}{Z_{S1}+Z_{R1}} + \frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{R1}(Z_{S1}+Z_{R1})} \tag{8}$$

From equations 2 and 5

$$I_{S2} = -\frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{S1}(Z_{S1}+Z_{R1})} \tag{9}$$

From equations 2 and 6

$$I_{R2} = -\frac{E_S Z_{R1}+E_R Z_{S1}}{2Z_{R1}(Z_{S1}+Z_{R1})} \tag{10}$$

Comparison of the magnitude of I_{S1}, equation 7, with the three-phase short-circuit current (E_S/Z_{S1}) is obscured by the two different voltages E_S and E_R.

If $E_S = E_R$, equation 7 becomes:

$$I_{S1} = \frac{E_S}{2Z_{S1}} \tag{7a}$$

This same result may be obtained more easily by considering only the left-hand portion of Figure 12, from which equation 7a is obtained directly.

From equation 7a, it is seen that the positive-phase-sequence current during the phase-to-phase fault is one half its value during a three-phase fault at the same location. In a similar manner, it can be shown that the 2/1 ratio holds in regard to negative-phase-sequence current. The 2/1 ratio is modified slightly if the positive- and negative-phase-sequence impedances are unequal. Also, with regard to the positive-phase-sequence component, the 2/1 ratio can be modified in either direction by the load component, the first term of equation 7.

Comparison of equations 7 and 8 shows that the fault components have the same sign, indicating an internal fault, whereas the load components have different signs, indicating a through-current condition.

Appendix II. Network Output

Referring to Figure 13, windings N have one-third the number of turns of windings A and C, and tapped winding KN has K times the number of turns of winding N. For an unbalanced fault (that is, a fault not operating all three overcurrent relays, O),

$$E_c = K_c[I_c + \frac{(K-1)}{3}I_0] = K_c[I_c + (K-1)I_0] \tag{11}$$

$$E_a = K_a[I_a - (I_0/3)] = K_a(I_a - I_0) \tag{12}$$

where K_c and K_a are constants of proportionality.

By adjustment of $R3$, E_C lags E_a by 60 degrees.

$$E_C = \alpha - aE_a \tag{13}$$

where a is the vector operator which rotates a vector 120 degrees in the positive direction.

$$I_a = (I_1 + I_2 + I_0) \tag{14}$$

$$I_c = (aI_1 + a^2I_2 + I_0) \tag{15}$$

where I_1, I_2, and I_0 are positive-, negative-, and zero-phase-sequence components of I_a.

From equations 12, 13, and 14

$$E_C = K_a'(-aI_1 - aI_2) \tag{16}$$

From equations 11 and 15

$$E_c = K_c(aI_1 + a^2I_2 + KI_0) \tag{17}$$

By design, and adjustment of $R2$, $K_c = K_a'$, and the network output voltage

$$E = E_C + E_c = K_c[(a^2-a)I_2 + KI_0] = K_c[-j\sqrt{3}I_2 + KI_0] \tag{18}$$

With a balanced three-phase fault $I_2 = I_0 = 0$, and the operation of overcurrent relays O changes to another tap on $R2$, which is adjusted to reduce E_c by a factor k, or

$$E_c = kK_c(aI_1 + a^2I_2 + KI_0) = kK_caI_1 \tag{17a}$$

$$E_C = -K_a'aI_1 \tag{16a}$$

Again,

$$K_c = K_a'$$

Then

$$E = E_C + E_c = K_caI_1(k-1) \tag{18a}$$

Comparison of equations 18 and 18a

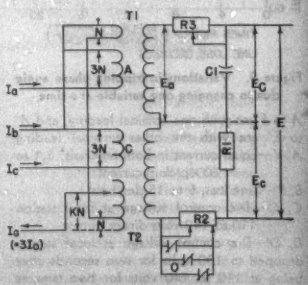

Figure 13. Connections and symbols (for Appendix II)

shows that the network output voltage is less as a function of I_1 during three-phase faults than it is as a function of I_2 during unbalanced faults. Consequently, the network is more sensitive to unbalanced faults than it is to three-phase faults.

Appendix III. Negative- and Zero-Phase-Sequence Currents

Negative-phase-sequence and zero-phase-sequence currents and their ratio during single- and two-phase-to-ground faults in terms of three-phase and single-phase-to-ground short-circuit currents now will be determined.

General Relations

Refer to Figure 14 for the negative-phase-sequence network, and if $Z_1 = Z_2$,

$$\frac{I_2}{I_2'} = \frac{I_{3\phi}}{I_{3\phi}'} \tag{19}$$

Where $I_{3\phi}'$ = total three-phase short-circuit current; $I_{3\phi} = C_1 I_{3\phi}'$ = three-phase short-circuit current from same direction as I_2.

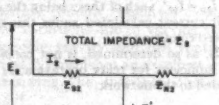

Figure 14. Negative-phase-sequence network (for Appendix III)

Referring to Figure 15 for the zero-phase-sequence network,

$$\frac{I_0}{I_0'} = \frac{I_G}{I_G'} \tag{20}$$

where

I_G' = total fault current on single-phase-to-ground fault

$I_G = C_0 I_G'$ = single-phase-to-ground fault current from same direction as I_0

Equations 19 and 20 apply to any type of fault during which those values are present. From equation 19

$$I_1 = I_1' \frac{I_{3\phi}}{I_{3\phi}'} \tag{21}$$

From equation 20

$$I_0 = I_0' \frac{I_G}{I_G'} \tag{22}$$

From equations 21 and 22

$$\frac{I_1}{I_0} = \frac{I_1'}{I_0'} \left(\frac{I_{3\phi} I_G'}{I_{3\phi}' I_G} \right) \tag{23}$$

SINGLE-PHASE-TO-GROUND FAULT

$I_0' = I_1'$

From equation 21

$$I_1 = I_1' \frac{I_{3\phi}}{I_{3\phi}'} = I_0' \frac{I_{3\phi}}{I_{3\phi}'} = \frac{I_{3\phi}}{I_{3\phi}'} \frac{I_G'}{3} = \frac{C_1 I_G'}{3} \tag{24}$$

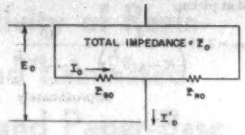

Figure 15. Zero-phase-sequence network (for Appendix III)

From equation 23

$$\frac{I_2}{I_0} = \frac{I_2'}{I_0'} \left(\frac{I_{3\phi} I_G'}{I_{3\phi}' I_G} \right) = \frac{I_{3\phi} I_G'}{I_{3\phi}' I_G} = \frac{C_1}{C_0} \tag{25}$$

TWO-PHASE-TO-GROUND FAULT

$$\frac{I_2'}{I_0'} = \frac{Z_0}{Z_1} = \frac{Z_0}{Z_1} + 2 - 2 = \frac{Z_0 + 2Z_1}{Z_1} - 2 \tag{26}$$

But $Z_0 + 2Z_1 = E/I_0'$ for single-phase-to-ground fault,

$$Z_0 + 2Z_1 = \frac{3E'}{I_G'} \tag{27}$$

From equations 26 and 27

$$\frac{I_2'}{I_0'} = \frac{3E}{Z_1 I_G'} - 2 = 3\left(\frac{I_{3\phi}'}{I_G'} \right) - 2 = R \tag{28}$$

From equations 23 and 28

$$\frac{I_2}{I_0} = \frac{I_2'}{I_0'} \left(\frac{I_{3\phi} I_G'}{I_{3\phi}' I_G} \right) = R \left(\frac{I_{3\phi} I_G'}{I_{3\phi}' I_G} \right) = R \frac{C_1}{C_0} \tag{29}$$

$$I_1 = \frac{E(Z_1 + Z_0)}{Z_1(Z_1 + 2Z_0)}$$

$$E_2 = E - I_1 Z_1 = E - \frac{E(Z_1 + Z_0)}{Z_1 + 2Z_0}$$

$$E_2 = \frac{EZ_0}{Z_1 + 2Z_0} = \frac{E}{(Z_1/Z_0) + 2} \tag{30}$$

From equations 26 and 28

$$\frac{Z_1}{Z_0} = \frac{1}{R} \tag{31}$$

From equations 30 and 31

$$E_2 = \frac{E}{(1/R) + 2} \tag{32}$$

$$I_2' = -\frac{E_2}{Z_1} = -\frac{E}{Z_1} \left(\frac{R}{1+2R} \right) = -I_{3\phi}' \left(\frac{R}{1+2R} \right) \tag{33}$$

From equations 19 and 33

$$I_2 = -I_{3\phi} \left(\frac{R}{1+2R} \right) = -C_1 I_{3\phi}' \left(\frac{R}{1+2R} \right) \tag{34}$$

From equations 29 and 34

$$I_0 = \frac{I_2}{R} \frac{C_0}{C_1} = -C_0 I_{3\phi}' \left(\frac{1}{1+2R} \right) \tag{35}$$

Ground current $= 3I_0 = -3C_0 I_{3\phi}' \left(\frac{1}{1+2R} \right)$

$$= -\frac{3I_{3\phi}' I_G}{I_G'} \left(\frac{1}{1+2R} \right) \tag{36}$$

*I_G' previously defined as applying to a single-phase-to-ground fault only.

Appendix IV. Operation During Ground Faults

Conditions during which sufficient negative-phase-sequence current is available for relay operation during ground faults will now be determined.

SINGLE-PHASE-TO-GROUND FAULT

From equation 24, Appendix III,

$$I_2 = \frac{C_1 I_G'}{3} = \frac{I_{3\phi}}{3} \frac{1}{(I_{3\phi}'/I_G')} \tag{37}$$

When $I_{3\phi}$ is just equal to the three-phase relay pickup (eight amperes), the magnitude of I_2 must be equal to or greater than the negative-phase-sequence pickup ($\sqrt{3}$ amperes) or

$$I_2 = \frac{8}{3} \frac{1}{(I_{3\phi}'/I_G')} \geq \sqrt{3}$$

$$\frac{I_{3\phi}'}{I_G'} \leq \frac{8}{3\sqrt{3}} = 1.5 \text{ (approximately)} \tag{38}$$

TWO-PHASE-TO-GROUND FAULT

From equation 34, Appendix III,

$$I_2 = I_{3\phi} \left(\frac{R}{1+2R} \right) = I_{3\phi} \left[\frac{3(I_{3\phi}'/I_G') - 2}{6(I_{3\phi}'/I_G') - 3} \right] \tag{39}$$

Again, I_2 in equation 39 must be equal to or greater than $\sqrt{3}$ when $I_{3\phi} = 8$ amperes.

$$8 \left[\frac{3(I_{3\phi}'/I_G') - 2}{6(I_{3\phi}'/I_G') - 3} \right] \geq \sqrt{3}$$

$$24(I_{3\phi}'/I_G') - 16 \geq 6\sqrt{3}(I_{3\phi}'/I_G') - 3\sqrt{3}$$

$$13.6\ (I_{3\phi}'/I_G') \geq 10.8$$

$$\frac{I_{3\phi}'}{I_G'} \leq 0.8 \text{ (approximately)} \tag{40}$$

Appendix V. Blind Spots

Conditions necessary to avoid blind spots during ground faults (when ground-current excitation is used) will now be determined. The network output from equation 18, Appendix II, is

$$E = K_2(-j\sqrt{3}I_2 + KI_0) \tag{18}$$

If it is assumed that I_2 can be at any angle relative to I_0, KI_0 will overcome $\sqrt{3}I_2$ when

$$KI_0 > \sqrt{3}I_2$$

or when

$$K > \sqrt{3}\left(\frac{I_2}{I_0} \right) \tag{42}$$

If (as an additional safeguard against failure to trip due to excessive phase displacement between the network outputs at the two terminals) it is specified that $(-j\sqrt{3}I_2 + KI_0)$ shall not be in excess of 45 degrees from I_0, at either terminal, KI_0 must be larger than $\sqrt{3}(I_2/I_0)$ by an additional multiplier, $\frac{1}{\sin 45^\circ} = \sqrt{2}$

$$KI_0 > \sqrt{2}\sqrt{3}I_2; \quad K > 2.45\left(\frac{I_2}{I_0} \right) \tag{43}$$

With the maximum available value of K as 21,

$$21 > 2.45\left(\frac{I_2}{I_0}\right)$$

or

$$\frac{I_2}{I_0} < 8.5 \text{ (approximately)} \quad (44)$$

But from equation 25, Appendix III, $I_2/I_0 = C_1/C_0$ or

$$\frac{C_1}{C_0} < 8.5 \text{ for a single-phase-to-ground fault} \quad (45)$$

From equation 29, Appendix III, $I_2/I_0 = (RC_1/C_0)$ or

$$\frac{C_1}{C_0}\left[3\left(\frac{I_{b\phi}'}{I_G'}\right)-2\right] < 8.5 \text{ for two-phase-to-ground fault} \quad (46)$$

Thus, if $I_{b\phi}'/I_G'$ is less than 1, equation 45 gives the limiting condition, whereas if $I_{b\phi}'/I_G'$ is greater than 1, equation 46 gives the limiting condition.

Appendix VI. Relay Pickup

Relay pickup in terms of ground current (when ground-current excitation is used) is determined as follows. From equation 18, Appendix II, the network output is

$$E = K_c(-j\sqrt{3}I_2 + KI_0) \quad (18)$$

For any condition for which I_2 and I_0 are known at pickup, E/K_c can be found. Knowing E/K_c, pickup in terms of I_G can be determined knowing only I_2/I_0.

The single-phase-to-ground single-end-feed pickup values given in Appendix VII are for a fault on the phase giving the highest pickup, that is, the phase for which I_2 and I_0 are most nearly in opposition. For a fault on phase b, I_2 (phase a being the reference phase) lags I_0 by 120 degrees. The quantity $-jI_2$ lags I_0 by 210 degrees ($I_2 = -ja^2I_0$), or 30 degrees from complete opposition. In magnitude, $I_2 = I_0$. By choosing any combination of K and ground current at pickup (for example, $K = 21$, $I_G = 0.5$), and by substitution in equation 18b,

$$E = K_c(-ja^2\sqrt{3}I_0 + KI_0)$$

$$= \frac{K_cI_G}{3}[(K - \sqrt{3}\cos 30)^2 + (\sqrt{3}\sin 30)^2]$$

$$= \frac{K_c\,0.5}{3}[(21 - 1.5)^2 + (\sqrt{3}/2)^2]$$

$$E/K_c = 3.25$$

With double-end-feed, and with the assumption that I_2 and I_0 can be in complete opposition,

$$E/K_c = -\sqrt{3}I_2 + KI_0 = \frac{I_G}{3}\left(K - \sqrt{3}\frac{I_2}{I_0}\right)$$

$$I_G = \frac{E}{K_c}\frac{3}{\left(K - \sqrt{3}\dfrac{I_2}{I_0}\right)}$$

and at pickup

$$I_{GPU} = 3.25\frac{3}{\left(K - \sqrt{3}\dfrac{I_2}{I_0}\right)} = \frac{10}{K - \sqrt{3}\dfrac{I_2}{I_0}}$$

approximately (41)

Appendix VII. Detailed Application of Relay System

The application of the relay system can be reduced to the following steps:

1. Determination of margin above pickup during three-phase faults with minimum generating conditions.
2. Determination of margin of the negative-phase-sequence current, above pickup, during single-phase-to-ground and two-phase-to-ground faults.
3. The determination of K (the proportion of added excitation from I_0) to avoid blind spots if sufficient negative-phase-sequence current is not available in 2.
4. If I_0 is used, the determination of relay pickup in terms of ground current, to check the margin of fault current above pickup.

Three-Phase Faults

Under minimum generating conditions, determine the current in the relay at A (Figure 16) for a fault at 2. Repeat for the relay at B for a fault at 1. The three-phase pickup of the relay is eight amperes. If in either instance one of the currents is insufficient to operate the relay, assume sequential operation and determine the current at the questionable terminal with the opposite circuit breaker open. Hereafter, this note is not repeated but is assumed.

Phase-to-Phase Faults

It is not necessary to consider this type of fault, unless the incidence of three-phase faults is assumed negligible, since the relay system is more sensitive to phase-to-phase faults than to three-phase faults. The relay pickup for this condition is three amperes ($\sqrt{3}$ amperes negative-phase-sequence).

Ground Faults—Determination of I_2

In the determination of the available negative-phase-sequence current, it is necessary to know only the three-phase and single-phase-to-ground short-circuit currents which must be known in any overcurrent relay application.

For a single-phase-to-ground fault (equation 24, Appendix III):

$$I_2 = \frac{I_{b\phi}}{I_{b\phi}'}\frac{I_G'}{3} \quad (24)$$

where

I_G' = total ground amperes in single-phase-to-ground fault

I_G (used in equation 25 in this appendix) = portion of I_G' from terminal in question

Figure 16. Fault locations (for Appendix VII)

$I_{b\phi}'$ = total phase amperes in three-phase fault

$I_{b\phi}$ = portion of $I_{b\phi}'$ from terminal in question

With a single-phase-to-ground fault at 2 (Figure 16), determine the negative-phase-sequence current I_2 at terminal A from equation 24. Repeat for terminal B for a fault at 1.

For a two-phase-to-ground fault, repeat the determination of I_2 with this type of fault using equation 34 (from Appendix III).

$$I_2 = I_{b\phi}\left(\frac{R}{1+2R}\right) \quad (34)$$

where

$$R = \frac{3I_{b\phi}' - 2I_G'}{I_G'}$$

If there is sufficient negative-phase-sequence current available during all of these conditions, no further calculation is necessary (that is, it is not necessary to consider the introduction of I_0 into the network). If I_2 is to be checked after the opening of the first breaker, the same formulas can be used with $I_{b\phi} = I_{b\phi}'$, each of these being the short-circuit current calculated under this single-end-feed condition.

If I_2, as so determined, is not considered to be sufficient for relay operation, I_0 must be added to the network.

Ground Faults—Determination of K

With a single-phase-to-ground fault at 2 (Figure 16), determine the ratio I_2/I_0 at terminal A from equation 25 as given here (from Appendix III):

$$\frac{I_2}{I_0} = \frac{I_G'I_{b\phi}}{I_GI_{b\phi}'} \quad (25)$$

Repeat for terminal B with a fault at 1.

Repeat for two-phase-to-ground faults using equation 29 from Appendix III.

$$\frac{I_2}{I_0} = \left(\frac{I_G'I_{b\phi}}{I_GI_{b\phi}'}\right)R \quad (29)$$

By use of the highest of the four values of I_2/I_0 found, choose an available value of K (6, 8, 11, 15, or 21) so that

$$K > 2.45\frac{(I_2)}{(I_0)} \text{ (from Appendix V)} \quad (43)$$

It is noted from equation 43 that if it is necessary to introduce I_0 into the network, ground current must be available from both terminals. The relay system is not applicable if an internal fault will, under any circumstances, draw I_0 from one direction only and I_2 from the other direction, unless negative-phase-sequence currents alone are sufficient for at least sequential relay operation.

Ground Faults—Determination of Pickup in Terms of Ground Current

If it is assumed that the negative-phase-sequence current can be at any phase angle relative to the zero-phase-sequence current, the resultant pickup in terms of ground cur-

The Electrical Resistivity of Resin-Treated Wood and Laminated Hydrolyzed-Wood and Paper-Base Plastics

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NONMEMBER AIEE

WOOD in the dry state is an excellent dielectric, having a volume resistivity in the range of 3×10^{17} to 3×10^{18} ohm-centimeters.[2] The resistivity decreases rapidly, however, with an increase in moisture content, reaching values of 10^8 to 10^9 ohm-centimeters at the fiber-saturation point (30-per-cent moisture content on the basis of the dry weight of the wood).[5] This tremendous change in the electrical resistance of wood with changes in moisture content, which so overshadows the variations due to varying species and specific gravity and ash content of the wood,[4,6] furnishes an excellent means of measuring the moisture content of wood.[6,12]

The treatment of wood with aqueous phenol-formaldehyde resin-forming solutions according to the methods developed at the United States Forest Products Laboratory[7-11] has been shown to reduce greatly the moisture adsorption and swelling even under equilibrium conditions. Because of the reduced moisture content of resin-treated wood (*impreg*[10]) and the corresponding resin-treated compressed wood (*compreg*[11]) in equilibrium with any relative humidity, the electrical resistivity should be correspondingly increased. The data given in this report show that this is the case and that wood, hydrolyzed-wood sheet, and paper properly treated with resins are suitable for various dielectric uses even under relatively high-humidity conditions.

The electrical resistivity of normal wood and *impreg* and *compreg* of ten different species was determined on single sheets of veneer after kiln drying and in equilibrium with four different relative humidities. The changes in resistivity resulting from variations in resin content, degree of compression, and the presence of glue lines in laminated material were determined. The extent of surface resistivity was investigated for the resin-treated wood. The volume resistivities of a limited number of hydrolyzed-wood sheet specimens containing both aniline-furfural and phenol-formaldehyde resins, and laminated Mitscherlich sulphite paper treated with both water- and alcohol-soluble phenolic resins were also determined.

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Electrical Measurements

D-c resistivity measurements were made with a sensitive galvanometer used as an ammeter in an ammeter–voltmeter circuit as shown in the circuit diagram of Figure 1. The galvanometer had a sensitivity with the scale at four meters of 7.60×10^{-10} amperes per centimeter scale deflection. High potentials ranging from 20 to 300 volts were obtained with a d-c motor generator set. Low potentials, from 15 to 0.01 volts, were obtained from dry cells with the use of potential dividers. The apparatus was thus capable of measuring any resistance from 30 ohms to 4×10^{13} ohms.

All the switches were coated with ceresin wax, which has a high-surface resistivity, to minimize current leakage. Switches S_3, S_4, and S_7 were shielded by wrapping bare copper wires about the bases in three directions and connecting these to the circuit at α, thus leading any stray current around the galvanometer. To avoid confusion, these leads are not shown in Figure 1. In spite of these precautions, stray currents were found to be excessive in damp weather. Hence the apparatus was set up in a constant relative-humidity room held at 30-per-cent relative humidity and 80 degrees Fahrenheit. With these precautions the volume leakage of the system was reduced to the point that the conductivity was only about 5×10^{-13} ohms, which was insufficient to affect the results seriously.

The electrodes consisted of two rectangular brass plates, each with a surface area of 35.0 square centimeters and a brass guard rim one centimeter wide that fitted around the perimeter of one of the electrode plates with a 0.5-centimeter gap between the guard rim and the electrode. This, together with the other shield wires, was connected at α in Figure 1, so that any current flowing along the surface of the sample was led around the galvanometer.

The electrode plates were held against the sample by a screw clamp with hard rubber jaws. The clamp had a resistance of 2×10^{13} ohms, which was about ten times that of the highest resistance measured and from 100 to 1,000 times the usual resistance measured.

It was found that the resistance of a specimen varied inversely with the pressure applied to the electrodes at lower pressures, but above a pressure of 23 pounds per square inch the resistance change became negligible. The clamp was tightened to exceed this pressure for all the measurements.

The surface resistivity was measured with six bar electrodes ten centimeters long and one centimeter wide. Three parallel electrodes on each surface were paired opposite each other on the two faces of a specimen and bolted through holes in the specimens slightly larger than the bolts. The two outer bars on both surfaces were electrically coupled so that a flow of current occurred from the cen-

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rent ($3I_0$) may be increased if I_3 opposes I_0. The resultant pickup may be as high as 3.25 (Appendix VI) times the single-end-feed ground-fault pick-up values ($3I_0 = 2.2$, 1.55, 1.05, 0.75, or 0.5 amperes corresponding respectively to the values of K just given).

The ground-fault currents ($3I_0$) are the following:

Single-phase-to-ground $= I_g$ (one of the known currents)

$$\text{Two-phase-to-ground} = \frac{3I_{gg}'I_g}{I_g'}\left(\frac{1}{1+2R}\right) \quad \text{(from Appendix III)} \quad (36)$$

If the available ground currents calculated are less than 3.25 times the single-end-feed pickup, the actual pickup in terms of ground current (I_{GPU}) can be calculated by means of equation 41, Appendix VI.

$$I_{GPU} = \frac{10}{K - \sqrt{3}\left(\frac{I_3}{I_0}\right)} \quad (41)$$

If the available ground current is not sufficient to operate the relay (pickup calculated from equation 41), the value of K may be increased. K should not be increased unnecessarily, since a higher value of K means higher burden on the current transformers.

References

1. A CARRIER-CURRENT PILOT SYSTEM OF TRANSMISSION LINE PROTECTION, A. S. Fitzgerald. AIEE TRANSACTIONS, volume 47, 1928, pages 22–9.

2. A NEW CARRIER RELAYING SYSTEM, T. R. Halman, S. L. Goldsborough, H. W. Lensner, A. F. Dromp. AIEE TRANSACTIONS, volume 63, 1944. August section, pages 568–72.

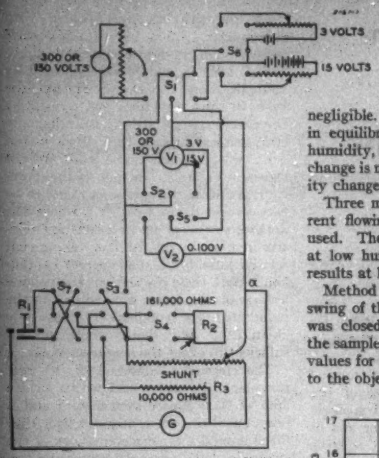


Figure 1. Wiring diagram of resistivity equipment

tral to the two outer bars on both faces across a 0.10-centimeter gap. The surface resistivity r_s was calculated from the equation $r_s = 4R_s\frac{l}{d}$ where R_s is the measured surface resistance, l is the bar length, and d is the distance between the bars.

The wood specimens were cut from $^1/_{16}$-inch rotary-cut veneer (0.16 centimeter). The *compreg* specimens were one third to one half as thick, as a result of compression. The hydrolyzed-wood sheet and laminated-paper plastic specimens varied from 0.06 to 0.15 centimeter in thickness.

The specimens were kiln dried or conditioned in humidifiers containing saturated salt solutions. At 30 degrees centigrade the barium chloride, sodium chloride, manganese chloride, and magnesium chloride used gave 90.8-, 75.8-, 53.9-, and 32.7-per-cent relative humidity, respectively.

The specimens were moved from the lower to the higher relative-humidity conditions. The resistivity–moisture content curves to follow are hence all adsorption curves.

Resistivity measurements made after different times of humidification indicated that moisture equilibrium was obtained in all cases in 20 days or less. The measurements recorded in the following figures were all made after 30 days' humidification to insure definitely the attainment of equilibrium conditions.

All the volume-resistivity measurements were made in the 30-per-cent relative-humidity room as rapidly as possible after the specimens were removed from the humidifiers, which required about three minutes. During this time the moisture-content change for all the resin-treated specimens was practically negligible. Even in the untreated wood in equilibrium with 90-per-cent relative humidity, for which the moisture-content change is most rapid, the volume-resistivity change was only five to ten per cent.

Three methods of measuring the current flowing through the samples were used. They gave widely varying results at low humidities, but closely checking results at high humidities (Figure 3).

Method 1 observed the maximum swing of the galvanometer as the switch was closed and current surged through the sample. This method gave the lowest values for the resistivity. It was subject to the objection that the electrode plates

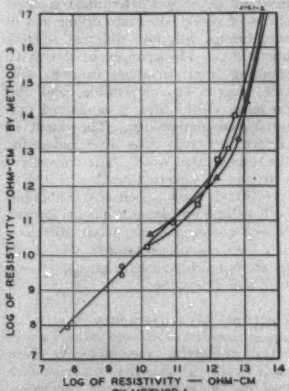


Figure 2. Logarithm of average volume resistivity of ten species of wood (basswood, yellow birch, cottonwood, Douglas fir, white fir, sweetgum, Western hemlock, yellow poplar, redwood, and Sitka spruce), and of *impreg* and *compreg* made therefrom determined by method 3 versus the corresponding values determined by method 1

○ Untreated wood
△ *Impreg*
□ *Compreg*

acted as a capacitor and so contributed to the magnitude of the swing.

Method 2 observed the first steady deflection of the galvanometer after the switch was closed. The polarity of the electrodes was changed by means of the reversing switch S_7 (Figure 1), and the average of the readings for the flow of current in the two directions was used. The value of the resistivity obtained by this second method probably approximated most nearly the true value of the resistivity. The chief difficulty was that some samples polarized so rapidly that no steady deflection could be observed.

Method 3 was that used by the American Society for Testing Materials,[1] namely, that of reading the galvanometer deflection after the current had been flowing through the sample for one minute. This, however, gave a value of the resistivity which had been considerably increased by polarization.

By plotting corresponding values of the resistivity obtained by methods 1 and 3 against each other and extrapolating the curve, it was possible to determine method-3 resistivities from method-1 resistivities that were too high to measure directly but which were still within the range of the apparatus for method 1 (Figure 2). This procedure was used to obtain method-3 resistivities for the kiln-dried samples before they were exposed to the 32.7-per-cent relative humidity. The kiln-dried samples contained from 0.5 to 2-per-cent moisture and had method-3 resistivities of the order of 10^{16} ohm-centimeters.

Volume Resistivity of Wood

Volume-resistivity measurements were made on matched specimens of the ten

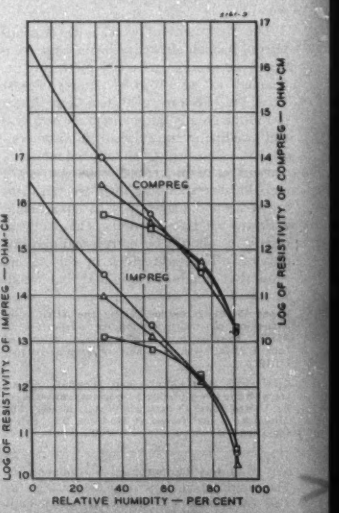


Figure 3. Logarithm of the average volume resistivity of *impreg* and *compreg* made from ten species of wood (basswood, yellow birch, cottonwood, Douglas fir, white fir, sweetgum, Western hemlock, yellow poplar, redwood, and Sitka spruce), determined by three methods versus the equilibrium relative humidity

□ Method 1
△ Method 2
○ Method 3

species of wood, listed in Figure 2, in the untreated form and made up into *impreg* and *compreg* by previously described methods[9-11] using Bakelite Corporation resinoid *BR*5995. Both the *impreg* and the *compreg* were cured in a hydraulic press for 45 minutes at 300 degrees Fahrenheit, *impreg* under a negligible pressure and *compreg* under 1,250 pounds per square inch. The resin contents of the different specimens varied from 31 to 57 per cent on the basis of the weight of the dry untreated wood. It will be shown later (Figure 7) that within this range the volume resistivity changes but slightly with variations in resin content. Because of this and the fact that the variation in volume resistivity with species was practically within the range of experimental error, average values for all the species are plotted in Figures 2 through 5.

Figure 3 gives a comparison between the average volume resistivities of *impreg* and *compreg* determined by the three different methods plotted against the equilibrium relative humidity. Variations between the values obtained by the three methods are appreciable only for low relative humidities at which the resistivities are relatively high. The resistivities given in the following figures were all determined by method 3, that recommended by the American Society for Testing Materials.[1]

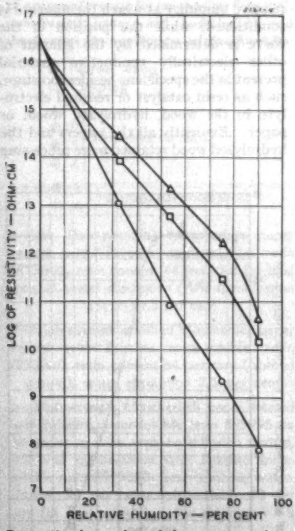


Figure 4. Logarithm of the average volume resistivity (method 3) of ten species of wood (basswood, yellow birch, cottonwood, Douglas fir, white fir, sweetgum, Western hemlock, yellow poplar, redwood, and Sitka spruce), and of *impreg* and *compreg* made therefrom versus the equilibrium relative humidity

○ Untreated wood
△ *Impreg*
□ *Compreg*

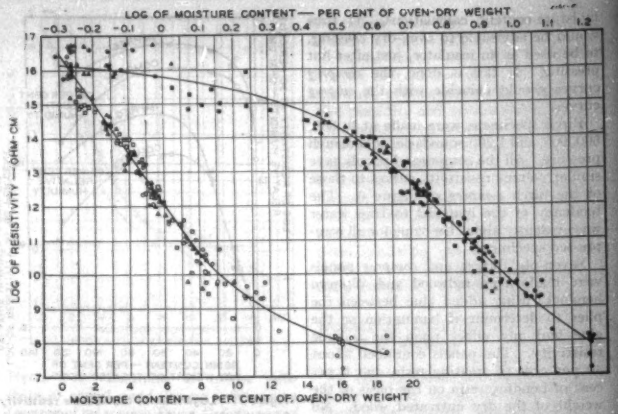

LOG OF MOISTURE CONTENT — PER CENT OF OVEN-DRY WEIGHT
LOG OF RESISTIVITY — OHM-CM
MOISTURE CONTENT — PER CENT OF OVEN-DRY WEIGHT

Figure 5. Logarithm of the average volume resistivity (method 3) of ten species of wood (basswood, yellow birch, cottonwood, Douglas fir, white fir, sweetgum, Western hemlock, yellow poplar, redwood, and Sitka spruce), and of *impreg* and *compreg* made therefrom versus the moisture content

Per cent moisture content:
○ Untreated wood
△ *Impreg*
□ *Compreg*
Log per cent moisture content:
● Untreated wood
▲ *Impreg*
■ *Compreg*

Figure 4 gives the logarithm of the average resistivity for untreated wood, *impreg*, and *compreg*, made from ten different species, plotted against the equilibrium relative humidity. The resistivity of *impreg* is slightly higher than that of *compreg* and considerably higher than that of normal wood under the same relative-humidity conditions. The three curves, when extrapolated to zero relative humidity, give practically identical resistivities. The reason for this is shown in Figure 5, in which the same resistivity data are plotted against the moisture content. On this basis, the values for the three materials fall on a single curve, indicating that the resistivity depends primarily upon the moisture content. Differences between the curves of Figure 4 merely show differences in hygroscopicity (or apparent hygroscopicity, as will be shown later) of the three materials.

Figure 6 gives the volume resistivity of birch *impreg* and *compreg*. The values are very similar to the average values for the ten species given in Figures 4 and 5.

Figure 7 shows the effect of the resin content of both *impreg* and *compreg*, made from two different species, upon the volume resistivity at two different relative humidities. The resistivity increases rapidly with an increase in resin content up to about 30-per-cent resin content on the basis of the dry weight of the wood, and then remains relatively constant, but again decreases with very high resin content. The original increase is due to the decrease in hygroscopicity with increasing resin content.[7] On the other hand, electrolyte introduced with the resin will decrease the resistivity as the proportion of resin to wood increases. This decrease in resistivity is evidently small, compared to the increase in resistivity due to decreased hygroscopicity up to about 30-per-cent resin content. Above this resin content the decrease in hygroscopicity is small.[7] Between this resin content and one of 70 per cent the two effects evidently neutralize each other, whereas above 70-per-cent resin content the effect of the electrolyte predominates.

The rapid decrease in the hygroscopicity in both the *impreg* and the *compreg* with increasing resin content up to about 30 per cent, followed by a smaller decrease in hygroscopicity with a further increase in resin content, is clearly shown in Figure 8 for the specimens of Figure 7.

Figures 4 through 8 all show that *impreg* has a higher resistivity than *compreg* for the same relative humidity, although it is the same for the same moisture content. This difference between the two materials makes it appear that *compreg* is more hygroscopic than *impreg*. This explanation does not seem so probable as the possible entrapping of water within the resin of the *compreg* which was not lost in the curing or in the kiln drying of these samples prior to humidification, but which is lost during the final oven drying to determine the dry weight for

moisture-content calculations. It thus would be advisable to oven-dry *compreg*, to be used as an insulator, just after hot pressing. If this is done, the *compreg* curves should coincide with the *impreg* curves.

Birch specimens were made at 0, 300, 600, 900, and 1,200 pounds per square inch pressure. All the compressed panels gave similar volume-resistivity curves to those of the birch *compreg* of Figure 6. The tendency of the material to trap water was evidently about the same for all compressed specimens.

Seven-ply *impreg* and *compreg* panels were made from redwood and Western hemlock, using added glue between the plies to determine if lamination or the glue had any effect upon the volume resistivity. The panels contained about 40 per cent of treating resin and 9 per cent of bonding resin on the basis of the weight of the dry untreated wood. No significant differences in the volume resistivity between these specimens and the single-ply specimens were observed.

Surface Resistivity of Wood

Figure 9 shows the relationship between the surface resistivity and the relative humidity to which oven-dry samples of *impreg* and *compreg* were exposed for 15 minutes. The relative humidity of the chamber in which the measurements were made was controlled by blowing air over different concentrations of sulphuric acid. Relative humidities corresponding to different concentrations were taken from tables given by Wilson.[13] Fifteen minutes' exposure was adequate to allow the surface film to come to approximate

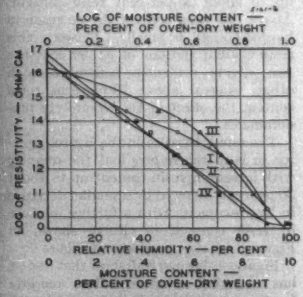

LOG OF MOISTURE CONTENT — PER CENT OF OVEN-DRY WEIGHT
LOG OF RESISTIVITY — OHM-CM
RELATIVE HUMIDITY — PER CENT
MOISTURE CONTENT — PER CENT OF OVEN-DRY WEIGHT
I
II
III
IV

Figure 6. Logarithm of the volume resistivity (method 3) of yellow birch *impreg* and *compreg* versus the equilibrium relative humidity and the moisture content

Resistivity of birch *impreg* and *compreg*

I	○ *Impreg*	relative humidity
II	● *Compreg*	
III	△ *Impreg*	log of moisture content
	▲ *Compreg*	
IV	□ *Impreg*	moisture content
	■ *Compreg*	

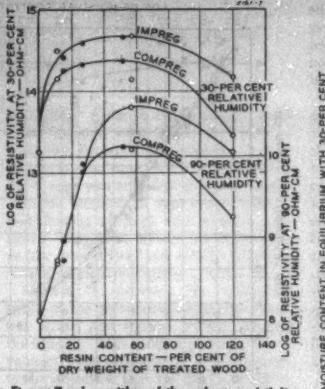

LOG OF RESISTIVITY AT 30-PER CENT RELATIVE HUMIDITY — OHM-CM
LOG OF RESISTIVITY AT 90-PER CENT RELATIVE HUMIDITY — OHM-CM
IMPREG
COMPREG
30-PER CENT RELATIVE HUMIDITY
90-PER CENT RELATIVE HUMIDITY
RESIN CONTENT — PER CENT OF DRY WEIGHT OF TREATED WOOD

Figure 7. Logarithm of the volume resistivity (method 3) of white fir and yellow birch *impreg* and *compreg* at two different relative humidities versus the resin content

○ White fir
⊕ Yellow birch

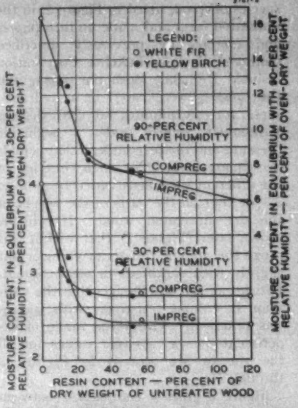

LEGEND:
○ WHITE FIR
⊕ YELLOW BIRCH
90-PER CENT RELATIVE HUMIDITY
30-PER CENT RELATIVE HUMIDITY
COMPREG
IMPREG
MOISTURE CONTENT IN EQUILIBRIUM WITH 30-PER CENT RELATIVE HUMIDITY — PER CENT OF OVEN-DRY WEIGHT
MOISTURE CONTENT IN EQUILIBRIUM WITH 90-PER CENT RELATIVE HUMIDITY — PER CENT OF OVEN-DRY WEIGHT
RESIN CONTENT — PER CENT OF DRY WEIGHT OF UNTREATED WOOD

Figure 8. Equilibrium moisture content of white fir and yellow birch *impreg* and *compreg* at two different relative humidities versus the resin content

○ White fir
⊕ Yellow birch

equilibrium without causing the volume resistivity to decrease to the point where it would affect the results appreciably. During this period two to three check readings were made, using the first steady galvanometer deflection. The specimens were freshly dried before exposure to the next higher relative humidity. No difference between *impreg* and *compreg* was observed; hence a single curve was plotted for both. Below a relative humidity of 40 per cent the surface resistivity is so small that it becomes of the same order as the volume resistivity, so that an appreciable part of the current flow is through the specimens. The curve shows that volume resistivity measurements made in a 30-per-cent relative-humidity room are inappreciably affected by the surface conductivity. Listray[3] similarly found that the surface resistivity of several different dielectrics became constant below a relative humidity of about 40 per cent.

Volume Resistivity of Paper and Hydrolyzed-Wood Laminates

The volume resistivities of resin-treated paper and hydrolyzed-wood sheets are given in Figures 10 and 11, together with the average values for normal wood and *compreg*. When plotted against the relative humidity (Figure 10) all the values fall between those for normal wood and for *compreg*. When plotted against the moisture content (Figure 11), most of the values fall on a single curve below the composite curve for wood, *impreg*, and *compreg*. It appears that the position of a point on one of the curves of Figure 11 is determined by the hygroscopicity and the relative humidity at which the material is conditioned, while the position of the curve is determined by the amount of other electrically conductive material present in the specimens besides moisture, such as resin catalyst or residual electrolyte in the wood, hydrolyzed wood, or paper. Evidently all the papers and the hydrolyzed wood retained more processing

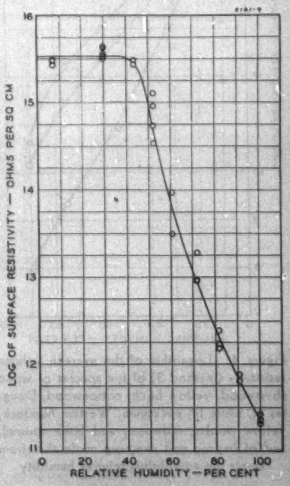


Figure 9. Logarithm of the surface resistivity of several species of *compreg* versus the atmospheric relative humidity

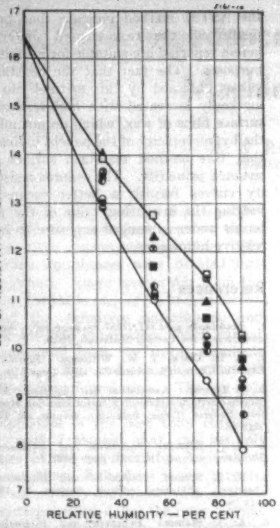
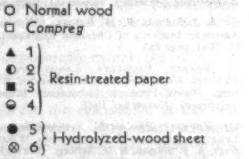


Figure 10. Logarithm of the volume resistivity of *compreg* (average for ten species, Figure 4), resin-treated paper, and hydrolyzed-wood sheet versus the equilibrium relative humidity



1—Soft (low-strength) Mitscherlich paper treated with Bakelite spirit-soluble resin *BR*13850, resin content 44 per cent (of total weight), water absorption (*AAF* specification 15065) 1.5 per cent

2—High-strength modified Mitscherlich paper treated with Bakelite spirit-soluble resin *BR*13850, resin content 34 per cent (of total weight), water absorption 7.5 per cent

3—High-strength Mitscherlich paper treated with Bakelite water-soluble resin *BR*5995 on the paper machine with no diffusion period, followed by treatment with Bakelite spirit-soluble resin *BR*13850, resin content, water-soluble, 20 per cent; spirit-soluble 13 per cent (of total weight), water absorption 1.3 per cent

4—High-strength Mitscherlich paper (same as 3) treated only with Bakelite water-soluble resin with no diffusion period; resin content 35 per cent (of total weight)

5—Hydrolyzed-wood sheet containing 15 per cent (of total weight) of aniline–furfural

6—Hydrolyzed-wood sheet containing 15 per cent (of total weight) of Bakelite water-soluble resin *BR*5995

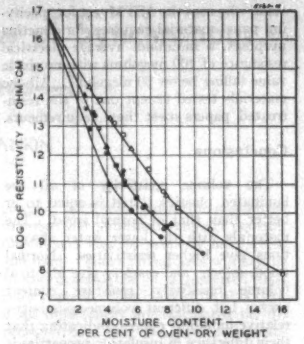


Figure 11. Logarithm of volume resistivity of normal wood, *impreg* and *compreg* (average of ten species, Figure 4), resin-treated paper and hydrolyzed-wood sheet, versus the moisture content. For key to specimens see Figure 10

electrolyte than the normal electrolyte content of the wood, or the resins used contained more electrolyte. It is of interest that all the curves extrapolate to the same volume resistivity at zero relative humidity and zero moisture content. This might be expected, as the conductivity of any contained electrolyte is largely dependent upon moisture being present. Hydrolyzed-wood sheet 5 with an aniline–furfural plasticizer is the only treated material tested which does not contain a phenolic resin. Its definitely poorer electrical insulating properties may be due either to the difference in resins used or the presence of more electrolyte.

Resistivity According to ASTM Method

A few measurements of electrical resistance were made by the American Society for Testing Materials method.[1] This test determines the resistance between adjacent binding posts that are bolted through panel specimens. Three binding posts were bolted through 2 1/2-by-4-inch specimens, of thicknesses shown in Table I, one at the center and two at 1 1/4 inches (center to center) from the central binding post in the length direction of the specimen and equally distant from each of the edges. Brass washers 9/16 inch in outside diameter were used on both surfaces of the bolted-in binding posts, giving a distance between adjacent washers on the surfaces of the specimens

Table I. Electrical Resistance According to the ASTM Method

Material	Resin*	Resin† Content, Per Cent	Thickness, Inch	Cycle	Electrical Resistance, Megohms
Birch *impreg*	*BR*5995	28.7	0.060	1	5,605
				2	6,490
Cottonwood *compreg*	*BR*15100	21.8	0.252	1	146
Cottonwood *compreg*	*BR*15100	21.8	0.074	1	317
				2	439
				3	412
Hydrolyzed-wood sheet	*BR*5995	15.0	0.043	1	13,300
Hydrolyzed-wood sheet	*BR*5995	15.0	0.065	1	1,890
				2	1,020
Hydrolyzed-wood sheet	Aniline–furfural	15.0	0.059	1	550
Soft (low-strength) Mitscherlich paper	*BR*13850	44.0	0.034	1	2,035
High-strength Mitscherlich paper	*BV*16303	36.9	0.145	1	5
				2	5
High-strength Mitscherlich paper (waxed surfaces)‡	*BV*16303	36.9	0.142	1	3,560
				2	7,120
High-strength Mitscherlich paper	*BV*16526	36.0	0.256	1	100
				2	110
				3	95
High-strength Mitscherlich paper	*BV*16526	36.5	0.132	1	82
				2	100
High-strength Mitscherlich paper (waxed surfaces)‡	*BV*16526	36.5	0.130	1	279,000
				2	39,800

* All resins but aniline–furfural are Bakelite Corporation resins.

† Resin content is on the basis of total weight of product. The resin content of the *impreg* and the *compreg*, on the basis of the dry weight of the untreated wood, on which basis they are normally expressed, are 43.3 and 28.0 per cent, respectively.

‡ The waxed specimens were coated with a thin film of wax by dipping the heated panels in cooler molten wax. The films were so thin that they were barely perceptible to the eye.

of 11/16 inch. The specimens were dried for seven hours at 160 degrees Fahrenheit according to the ASTM specifications and then exposed to a relative humidity of 90.5 ± 0.5 per cent for 96 hours at 80 degrees Fahrenheit (specified 87 degrees Fahrenheit ± 2 degrees Fahrenheit). Resistance measurements were made using the previously described apparatus. The results are shown in Table I. The insulation resistances are the averages of values obtained between adjacent pairs of binding posts. Most of the specimens were heated a second time for seven hours at 160 degrees Fahrenheit and again humidified for 96 hours to give second-cycle measurements. In some cases third-cycle tests were made. The agreement between the values for the different cycles was quite good for all materials tested except when waxed specimens were used. The *impreg* and the hydrolyzed-wood sheet plasticized with phenolic resin gave the highest electrical resistance values of the unwaxed specimens. The soft readily penetrated paper (number 1, Figure 10) gave the highest values of the treated but not waxed papers. The high-strength paper plastic made with *BV*16303 resin gave the lowest values while the high-strength paper plastic made with *BV*16526 gave intermediate values. The low values obtained with the *BV*16303 resin are probably due to the electrolyte content of the resin. The *compreg* values are not so high as they might have been if the material had contained more resin, as is evident in Figure 7. The waxed specimens gave high but not so consistent results. Differences are probably due to slight imperfections of the surface films. Although considerable wax drained off the specimens while heating prior to the second-cycle measurements, the electrical resistances were still high on the second measurement.

A large manufacturer of electrical material who uses the ASTM test for specifying panel material requires, for exacting purposes, a minimum average electrical resistance of 100 megohms with no single value falling below 60 megohms. All the materials tested except one of the resin-treated papers meet these requirements.

Conclusions

The volume resistivity of all the laminated plastics tested is equal to or better than that of normal wood. The materials with the lower water absorptions give higher resistivities. Normal wood, *impreg*, and *compreg* give identical volume - resistivity – moisture - content curves but different volume-resistivity–relative-humidity curves, indicating that their difference in insulating properties is due to differences in hygroscopicity. *Impreg* and *compreg* have volume resistivities about ten times that of normal wood at 30-per-cent relative humidity and about 100 to 1,000 times that of normal wood at 90-per-cent relative humidity, the *impreg* values tending to be somewhat greater than the *compreg* values. Resin contents in the range of 35 to 70 per cent have a negligible effect in changing the volume resistivity of *impreg* and *compreg*.

The surface resistivity at relative humidities below about 40 per cent is sufficiently small to be ineffective in controlling the insulating properties. The insulating properties of dry material exposed to higher relative humidities are largely determined by surface conductivity effects.

The volume resistivities of the laminated-paper plastics and hydrolyzed-wood plastics tested are somewhat lower than the values for *impreg* and *compreg*. This is, in part, due to greater hygroscopicity, but it also appears to be due to a somewhat greater electrolyte content.

Electrical-resistance measurements by the ASTM method indicate that practically all the resin-treated materials herein reported are suitable for insulating purposes. The fact that the resistance values obtained by this method can be markedly increased with high-resistance surface films of wax, which do not affect the hygroscopicity of the panels, indicates that this method measures surface resistance primarily. The volume-resistivity curves furnish a better means of judging the insulating value of the materials under prolonged exposure to high relative humidities.

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Per-Unit Impedances of Synchronous Machines—II

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THE preceding part[1] of this paper derived the generalized per-unit equations of the synchronous machine. The machine impedances were divided into two groups: those measurable from the stator terminals (x_d, x_d', r, and so forth), called the definitive impedances, and those internal impedances which cannot be measured from the stator terminals (X_{afd}, X_{ffd}, R_{ffd}, and so forth), called the nondefinitive impedances. The per-unit values of the definitive impedances are independent of the base rotor currents, but part I showed that the per-unit values of the nondefinitive impedances are functions of the base rotor currents, and accordingly are subject to misuse and misinterpretation unless the rotor-current bases are explicitly defined. These rotor-current bases and their corresponding base-current ratios are the fundamental quantities in any per-unit system, and this concluding part II is devoted to a fuller exposition of the base-current ratios of the more important per-unit systems.

To a considerable extent, the subject of base-current ratios is of primary interest only to the design engineers directly responsible for the calculation of the per-unit impedances. They must continuously guard against any inadvertent change of base during the analysis of new rotor circuits, since this would result in an impedance not in accord with the other rotor circuits. However, the application engineer also is directly interested in base-current ratios, because:

1. Such knowledge is necessary in order that he may be assured that all the per-unit impedances are in accord.

2. In many applications it is of advantage to introduce new bases or to use impedances calculated on some other base.

One specific base-current ratio is defined and evaluated in this paper, and its adoption or use as a preferred base in the calculation of per-unit impedances is suggested. Such standardization is essential in order that published values of per-unit impedances may be properly interpreted and used. Many advantages will accrue to the general use of a preferred base rotor current. The chief of these is that, if all impedances are calculated on the preferred base, they then become immediately available for use in general analysis or general equivalent circuits without fear of misapplication, and without the trouble and possible errors involved in determining the base current on which they were calculated and in converting this to a preferred base. As another example of the advantages of a preferred base rotor current, it should be noted that without recourse to a preferred base it is not possible when studying two per-unit impedance formulas to separate an improvement in the quality of the underlying analysis from a mere change in the rotor-current base.

It is obvious that the adoption of some preferred rotor-current base will have no effect upon vector diagrams as seen from the machine terminals. The base field current for such diagrams will continue to be that corresponding to normal open-circuit air-gap-line voltage, although the preferred base rotor currents will be used in calculating the impedance values.

This paper also brings together and evaluates the several base-current ratios which are found in contemporary literature; this evaluation is necessary in order to harmonize the various published per-unit impedance formulas. The method of converting all per-unit impedances to preferred-base impedances is evident from the expressions given in "Results", part I.

Suggested Preferred Bases

It is unnecessary to discuss the stator bases since by universal practice these are taken as the name-plate values (e_{a0}, i_{a0}, L_{a0}, x_{a0}). No corresponding universal practice exists in the selection of the rotor base quantities, and the adoption of some base-current ratio as a preferred standard for use in the calculation of machine impedances would be of advantage.

The base field current which in the author's experience offers the most advantages is that field current which will induce in each stator phase a voltage equal to $x_{ad}i_{a0}$. This will hereinafter be termed the "x_{ad}" base. Because of the advantages of this base itemized in the following, it is suggested that this x_{ad} base be adopted as a preferred standard:

(*a*). It makes X_{afd} numerically equal to x_{ad}, and at once makes unnecessary any further differentiation between these quantities.

(*b*). It makes the stator leakage reactance ($x_d - X_{afd}$) identical with the more familiar "leakage" reactance ($x_d - x_{ad}$). With a similar definition of the base current in the fictitious quadrature-axis field circuit, the stator leakage reactance is the same for both axes.

(*c*). It is in more common use at present than any other base (although implicitly only), and many of the present impedance formulas are based on it.

The base-current ratio for this field current is given by equation 1c. This expression is derived in the following section under definition 1.

$$\frac{I_{ffdo}}{(3/2)i_{ao}} = \frac{4}{\pi}\frac{A_{g1}}{F_{f1}}\frac{N}{K_pK_dP_1}\frac{1}{N_{ff}} \qquad (1c)$$

The foregoing definition of base current is also suggested for the additional rotor circuits of machines with one additional rotor circuit in each axis. The advantages are the same as those given for the base field current. The base-current ratio for the additional rotor circuits is then as given by equation 1d. This expression is also derived in the following section under definition 1.

$$\frac{I_{xdo}}{(3/2)i_{ao}} = \frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\frac{N}{K_pK_dP_1}\frac{1}{N_{xd}} \qquad (1d)$$

Synchronous machines with more than one additional rotor circuit in each axis require an involved analysis in which it is often advantageous to use specialized base quantities. For that reason it does not appear advisable to adopt preferred bases for multiple rotor circuits.

Specific Base-Current Ratios

The more important base-current ratios with practical advantages are given by the following four definitions. These definitions are summarized in Table I.

Definition 1: Let base field current I_{ffdo} be that current which will induce in each stator phase a voltage equal to $x_{ad}i_{ao}$; let base rotor-circuit current I_{xdo} be similarly defined. These are the base currents presented in the preceding section. These bases are hereinafter termed the x_{ad} bases.

With three-phase currents of magnitude i_{ao} in the stator, and with the rotor cir-

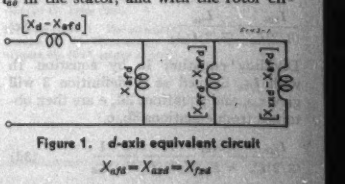

Figure 1. *d*-axis equivalent circuit

$X_{afd} = X_{azd} = X_{frd}$

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cuits open, the maximum of the fundamental-component flux density is as given by equation 1a.

$$\beta_{g0}(\max) = 0.4\pi \frac{4}{\pi} \frac{1.5 I_{a0} N}{K_p K_d P_1} \frac{2.54}{g} A_{d1} \quad (1a)$$

The corresponding phase voltage is $x_{ad} i_{a0}$. By definition 1, I_{fd0} is the field current which will give a fundamental-component density equal to equation 1a. The maximum of the fundamental component due to I_{fd0} is as given by equation 1b.

$$\beta_{gf}(\max) = 0.4\pi N_{fd} I_{fd0} \frac{2.54}{g} F_{d1} \quad (1b)$$

The base-current ratios of definition 1 are thus as given in equations 1c, d.

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{4}{\pi} \frac{A_{d1}}{F_{d1}} \frac{N}{K_p K_d P_1} \frac{1}{N_{fd}} \quad (1c)$$

$$\frac{I_{zd0}}{(3/2) i_{a0}} = \frac{4}{\pi} \frac{A_{d1}}{D_{dzz}} \frac{N}{K_p K_d P_1} \frac{1}{N_{zd}} \quad (1d)$$

It is evident from definition 1 that these x_{ad} bases make X_{afd} and X_{azd} numerically equal to x_{ad}.

Definition 2: Let base field current I_{fd0} be that current which will give a magnetomotive force per pole equal to the flat-topped armature reaction at normal stator current; let base current I_{zd0} be similarly defined. These bases are hereinafter termed the magnetomotive-force bases.

The base-current ratios can be written directly as in equations 2a, b.

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{N}{K_p K_d P_1} \frac{1}{N_{fd}} \quad (2a)$$

$$\frac{I_{zd0}}{(3/2) i_{a0}} = \frac{N}{K_p K_d P_1} \frac{1}{N_{zd}} \quad (2b)$$

Note that the base currents of these magnetomotive-force bases are easily evaluated since equations 2a, b do not contain pole-shape coefficients such as A_{d1}, F_{d1}, D_{dzz}, etc.

Definition 3: Let base field current I_{fd0} be the field current required to produce normal, open-circuit, air-gap-line stator voltage; let base current I_{zd0} be similarly defined. These bases are hereinafter termed the unit-voltage bases.

$$\psi_{a0} = 10^8 L_{afd} I_{fd0} = 10^8 L_{azd} i_{a0} \quad (3a)$$

Therefore

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{L_{a0}}{(3/2) L_{afd}} \quad (3b)$$

$$\frac{I_{zd0}}{(3/2) i_{a0}} = \frac{L_{a0}}{(3/2) L_{azd}} \quad (3c)$$

Dividing equation 1a by equation 1b with I_{fd0} defined as in definition 3 will give x_{ad}, and equations 3d, e are then obtained from equations 3b, c.

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{4}{\pi} \frac{A_{d1}}{F_{d1}} \frac{N}{K_p K_d P_1} \frac{1}{N_{fd}} \frac{1}{x_{ad}} \quad (3d)$$

$$\frac{I_{zd0}}{(3/2) i_{a0}} = \frac{4}{\pi} \frac{A_{d1}}{D_{dzz}} \frac{N}{K_p K_d P_1} \frac{1}{N_{zd}} \frac{1}{x_{ad}} \quad (3e)$$

The major advantage of the unit-voltage bases is that the stator-rotor mutual coupling coefficients are unity for the field circuit and the base additional rotor circuit.

Definition 4: Let the base rotor currents be defined so that the mutual impedances (X_{afd}, X_{azd}, X_{fzd}) for a machine with one additional rotor circuit are all equal. These bases are hereinafter termed the equal-mutuals bases.

$$X_{afd} = X_{azd} = X_{fzd} \quad (4a)$$

Equating 2a, 2b, and 3c of part I gives the base-current ratios in terms of the mutual inductances corresponding to equation 4a. These are evaluated in terms of design dimensions in equations 4b, c, d, and the base-current ratios of equations 4e, f thereby obtained.

$$L_{afd} = 3.19 \times 10^{-8} \frac{4RI}{P_1 g} \frac{N}{K_p K_d} N_{fd} F_{d1} \quad (4b)$$

$$L_{azd} = 3.19 \times 10^{-8} \frac{4RI}{P_1 g} \frac{N}{K_p K_d} N_{zd} D_{dzz} \quad (4c)$$

$$L_{fzd} = 3.19 \times 10^{-8} \frac{4RI}{g} N_{fd} N_{zd} D_{dzz} \gamma_{zd} \quad (4d)$$

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{N}{K_p K_d P_1} \frac{1}{N_{fd}} \frac{D_{dzz}}{D_{dzz} \gamma_{zd}} \quad (4e)$$

$$\frac{I_{zd0}}{(3/2) i_{a0}} = \frac{N}{K_p K_d P_1} \frac{1}{N_{zd}} \frac{F_{d1}}{D_{dzz} \gamma_{zd}} \quad (4f)$$

The equal-mutuals bases are of particular importance with machines having only one additional rotor circuit in each axis, as they result in the simple equivalent circuit of x_{la} in series with the parallel combination of X_{afd}, X_{fd}, and X_{zd}. It should be noted, however, that it is not now possible to replace X_{afd} by the more common x_{ad}, as these quantities are no longer equal. This fact seems to have been overlooked in the application of this simplified circuit.

Rotor Bases in Current Use

From the preceding analysis, it is evident that impedance formulas are subject to misuse unless the base-current ratios are known. A compendium of the base-current ratios of the present technical literature is needed in order to harmonize the various published results. This section offers the first step toward such a general compendium.

It is not necessary to study those publications which considered only the definitive impedances, since these are independent of the rotor bases. Examples of the papers which presented formulas for the rotor impedances as well as the stator quantities are Doherty and Shirley,[1] Linville,[2] and Kilgore.[4] The papers of Doherty and Nickle,[3] Park and Robertson,[4] Park,[7] and Waring and Crary[8] are illustrative of the papers on the operational machine equations. It is obvious that these two groups fail to include many important publications, but those listed are adequate to illustrate the need for a more complete survey.

Table I. Base Rotor Currents Used in the Calculation of Per-Unit Machine Impedances

Definition Characteristic	Base Field Current and Base Additional Rotor-Circuit Current Will
1. . x_{ad}	Induce in each stator phase a peak voltage equal to $x_{ad} i_{a0}$
2. . Magnetomotive force	Give in their respective windings a magnetomotive force equal to the flat-topped armature reaction at normal stator current
3. . Unit voltage	Induce in each phase normal open-circuit air-gap-line stator voltage
4. . Equal mutuals	Result in equal mutual impedances ($X_{afd} = X_{azd} = X_{fzd}$) for a machine with one additional rotor circuit

The base field current used by Doherty and Shirley may be derived from their expression for the increase in field magnetomotive force* due to the short-circuit current. It is the field current which will produce a magnetomotive force equal to $1/K_\phi$ times the flat-topped armature reaction, and differs only by the factor K_ϕ from the base field current of the magnetomotive-force base (definition 2). The corresponding base-current ratio is given by equation 5.

$$\frac{I_{fd0}}{(3/2) i_{a0}} = \frac{N}{K_p K_d P_1} \frac{1}{N_{fd}} \frac{1}{K_\phi} \quad (5)$$

Doherty and Shirley did not discuss any additional rotor circuits.

The base rotor currents used by Linville are explicitly defined as those which will produce in their respective windings a magnetomotive force equal to the flat-topped armature reaction. These are the base currents of the magnetomotive-force bases (definition 2), and the corresponding base-current ratios are evaluated in equations 2a, b.

Kilgore uses "effective" rotor leakage reactances defined as the quantities which when added to ($x_a - x_{ad}$) will give x_a' and x_a''. The base rotor currents are then such as to make the base stator–rotor mutual inductances numerically equal to x_{ad}. These are the base currents of the x_{ad} base (definition 1), and the corresponding base-current ratios are evaluated in equations 1c, d.

Doherty and Nickle specified as base field current that current which would produce normal open-circuit air-gap-line stator voltage. For a per-unit system with reciprocal mutual impedances, this

* Equation 2, page 1259, reference 2.

is the base field current of the unit-voltage base (definition 3), and the corresponding base-current ratio is evaluated in equation 3a.

A relatively large amount of machine analysis is based on the simplified circuit of Figure 1 although x_{ad} is commonly used in place of X_{afd}. The base currents which result in this circuit are the equal-mutuals bases of equations 4e, f (definition 4). Note that x_{ad} should not be used in place of X_{afd} as these two are equal only for the conditions of definition 1, the x_{ad} bases.

The base field current used by Park and Robertson was that which would give normal open-circuit air-gap-line stator voltage, but nonreciprocal mutual-impedance relations were used which resulted in the following expression for x_d'.

$$x_d' = x_d - \frac{X_{afd}}{X_{ffd}} * \qquad (6a)$$

If equation 6a is compared with equation 6b which is the more general expression for x_d',

$$x_d' = x_d - \frac{X'^2_{afd}}{X_{ffd}} ** \qquad (6b)$$

it is evident that satisfactory values of x_d' can be obtained only if X_{afd} is calculated on a base which recognizes the nonreciprocal mutual impedances.

The base current of Park is that of definition 3, but nonreciprocal mutual impedances are used which for all practical purposes restrict the application to machines with no additional rotor circuits.

The equations of Waring and Crary are general and dimensionally correct, and are not restricted to any specific base current. The base quantities are set by the design engineer in the calculation of the impedances. If it is desired to use the restricted operational equations of references 5 and 6 on machines with multiple rotor circuits, the necessary nonreciprocal mutual impedances can be best obtained by modifying the corresponding reciprocal mutual impedances of Waring and Crary as recently published by the author.[9]

To illustrate quantitatively the effect which the foregoing multiplicity of bases has upon the machine impedances, consider a machine with the design constants given by equation 7.

$$\left.\begin{aligned} K_\phi = 0.98 \quad \frac{4}{\pi}\frac{A_{d1}}{F_{d1}} = 1.10 \quad x_{ad} = 1.20 \\ D_{dx2} = 0.84 \quad D_{dx2y_{xd}} = 0.73 \end{aligned}\right\} \qquad (7)$$

Assume that x_d, X_{fd}, X_{ffd} are calculated by formulas using the base-current ratios of the x_{ad} bases (definition 1). If these same quantities are calculated for the same machine but by formulas based on the other ratios given in the foregoing review, the numerical values so obtained will be as shown in Table II. The values in this table are in per cent of the values calculated by formulas based on the x_{ad} bases.

Table II. Calculated Numerical Values for x_d, X_{afd}, and X_{ffd}

	x_d	X_{afd}	X_{ffd}
By the x_{ad} bases (definition 1)	100	100	100
By the magnetomotive force bases (definition 2)	100	91	83
By the unit-voltage bases (definition 3)	100	83	69
By the equal-mutuals bases (definition 4)	100	105	110
By equation 5	100	93	86

The magnitude of the possible error due to the misapplication of a per-unit impedance which has been calculated on a rotor-current base not explicitly defined is evident from Table II. The nonreciprocal relations of references 6 and 7 are not included in this table as their application is relatively rare. It is self-evident that this example is applicable only to the machine with the constants given by equation 7. The variations for other machines may be much greater or much less than those illustrated, depending on the design data.

Nomenclature

The nomenclature consists of the quantities given in the following plus the nomenclature of part I. All dimensions are in inches. As in part I, all quantities are in per unit except those in bold-face type which are in the physical ampere-inch system (ohms, henrys, and so forth). Quantities such as N, P_1, K_p, etc., for which it is obviously unnecessary to distinguish the ampere-inch values by a special script are in standard type only.

$\mathbf{a}_r$ = flat-topped armature reaction at base current

$$= \frac{1.5\sqrt{2}N i_{ao}}{K_p K_d P_1} \text{ ampere turns per pole}$$

A_{d1} † = factor by which the maximum flux density is multiplied to obtain the maximum of the fundamental component of flux density; machine excited by a sine-wave armature magnetomotive force in direct axis

$\frac{2}{\pi} D_{dxy}$ = factor by which the maximum flux density is multiplied to obtain the average density within the damper circuit of span $2y_{xd}$; machine excited by the damper circuit of span $2y_{xd}$ in the direct axis

D_{dx2} = same as A_{d1}, but with machine excited by the magnetomotive force of the xth additional rotor circuit in the direct-axis

F_{d1} ‡ = same as A_{d1}, but with machine excited by the magnetomotive force of the direct-axis field winding

g = effective air gap

K_p, K_d = pitch and distribution factors, respectively (greater than 1.0)

K_ϕ # = ratio of total flux per pole to the total fundamental flux per pole, at no load; machine excited by the magnetomotive force of the direct-axis field winding

l = machine stacked length, inches

N = stator series turns per phase

N_{fd} = turns per pole of field-winding circuit

N_{xd} = turns per pole of xth additional rotor circuit

P_1 = number of poles

R = stator bore radius, inches

x_d', x_d'' = transient and subtransient reactances, respectively

x_{la}, X_{lfd}, X_{lxd} = leakage reactances; armature, field, and xth additional rotor circuits; for use with equal-mutuals bases only

$2y_{xd}$ = span of xth additional rotor circuit, direct axis, in per unit of half pole pitch

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* Equation 20, reference 6.

** Equation 20, reference 8.

† See Figure 13, reference 10.

‡ This is the A_1 factor given by Figure 8, reference 10.

See Figure 10, reference 10.

Wound- and Dummy-Rotor Methods of Quality Control and Trouble Shooting of Induction-Motor Windings and Cores

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ONE OF THE FUNDAMENTAL principles in the solution of problems is the division of the large problem into several smaller ones. This principle is used throughout electric-motor engineering. One of the most common examples is the use of design constants or parameters. For instance, the complete characteristics of an induction motor are fixed and performance is determined if six constants are known.

r_1 = primary resistance
r_2 = secondary resistance
X = short-circuit reactance
X_o = open-circuit reactance
F_e = iron loss
$F+W$ = friction plus windage

If quality-control methods are used in the factory to prevent the values of these constants from straying beyond desired limits for a given design, then final assembly and test will not be plagued with rejections of defective motors.

It is the function of this paper to discuss means of controlling the variation of F_e iron loss and X_o open-circuit reactance. The open-circuit reactance is also a measure of the ampere turns necessary to set up the magnetic flux and a measure of the final magnetizing current and no-load amperes.

Because most induction motors have permanently short-circuited secondary windings in the form of squirrel-cage rotors, it has become customary to measure X_o and F_e by running the motors at synchronous speed. Under this condition, there is no current in the rotor of a polyphase motor, and a condition equivulent to open-circuited secondary winding exists. Actually, except for very small motors, satisfactory results are obtained at no-load speeds slightly under synchronism.

While the measurement of X_o and F_e on completed motors is necessary and desirable in quality control and trouble shooting, its obvious objection is that defective parts have not been eliminated at the source, but have continued through all the expensive and time-consuming manufacturing operations. Another very serious disadvantage is that small variations in the iron loss and ampere turns of the magnetic circuit are obscured and confused by ordinary variations in friction and air gap.

The stator is the most frequent source of troublesome variation, and one method of overcoming the difficulties mentioned is to test all stators in a fixture with rotor on bearings and duplicating normal operating conditions. The main objections to this method are its practical difficulties of construction, cost, and the necessity of applying it to a completely machined and ground stator.

Since the purpose is to duplicate the condition of open-circuited secondary winding, why not abandon the substitute method of running at synchronous speed and go directly to the open-circuited rotor? If only a single motor were involved, of course, there would be the expense of making a special rotor without squirrel cage. When hundreds or thousands of motors are in quantity production, however, the cost of a special "dummy" rotor for testing is negligible.

Dummy Rotors

Dummy test rotors are constructed exactly like the regular rotors, except without squirrel cage, and ground to the finished diameter of the regular rotor to obtain the regular air gap when testing finished stators. If it is necessary to provide means for holding the lamination in place, such means must not be conducting if it includes the magnetic circuit. The slots usually are left in to keep flux distribution as near normal as possible. Regular shafts are not necessary, because they do not rotate, but usually some sort of unfinished shaft is used to provide a convenient handle.

If polyphase power is applied to a polyphase stator and dummy rotor, the magnetic conditions differ somewhat from the open-circuit conditions in the regular motor. The first difference is that the high-frequency pulsation and surface losses caused by motor teeth and slot openings passing each other are not present. Partly offseting these, the rotor iron loss is at line frequency instead of slip frequency. The second difference is that the helpful effect of rotor currents in improving the sinusoidal flux distribution are not present. The nearer the stator winding is to having a sinusoidal distribution itself, the less will be this difference.

However, for quality control and trouble shooting, relative values and difference between good and bad stators are much more important than the actual value.

One of the difficulties in both no-load and dummy rotor tests with polyphase stators is the low power factor. This gives the difference of two large values when reading input by the two-wattmeter method. Since relative values are desired, and not actual, dummy-rotor test investigations very often are made with only single phase on the stator. This excites one phase only and gives about half the polyphase iron loss.

In general for comparative purposes, it is necessary to deduct only the primary copper loss before comparing readings; however a more accurate measure of the percentage variation is obtained when the constant-rotor iron loss also is deducted. The main difficulty in this is a means to measure it. Since it is usually small, a calculation from iron-loss curves may be

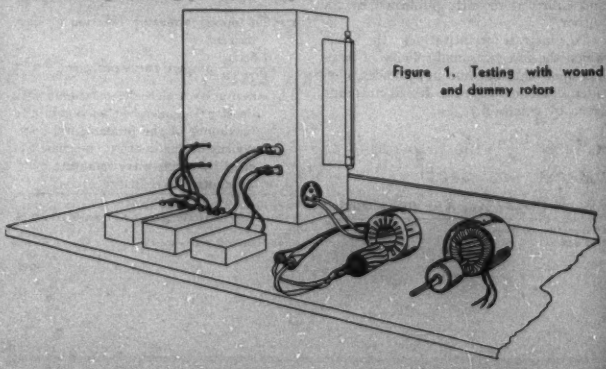

Figure 1. Testing with wound and dummy rotors

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sufficiently accurate. If a test value is desired, it may be necessary to put a temporary winding on the rotor and test with an oversize dummy stator as described later.

For quality control of polyphase wound-rotor motors or single-phase repulsion motors, readings may be taken on every new design with the brushes lifted, thus providing a dummy-rotor reading for comparison in case of future trouble. In case of regular squirrel-cage motors, the special dummy rotor must be provided. It is not necessary that a separate rotor be provided for every core stack. One rotor longer than any expected size is usually sufficient. In fact, it is better to have the rotor longer than the stator to eliminate the necessity for special care on axial location in testing.

The dummy-rotor method provides one of the most accurate tests of a wound stator that there is. Its accuracy may be increased even further for iron-loss or short-circuit investigation by using higher frequencies such as 500 or 1,000 cycles. Of course, any comparison to actual value disappears, and the tests become relative only.

Very often, the high-frequency test will provide a high-potential test between turns as a by-product.

Wound Rotors

We have mentioned the advantage of the dummy rotor over the running test in eliminating confusion due to variation in friction. However, the dummy-rotor test does require a winding in the stator with the possibility that expensive winding and machining operations may be completed before it is found that the stator cores have excessive iron loss. Under certain conditions it is difficult to distinguish between excessive iron loss and stator short circuits of one turn only. Also small variations in the number of stator turns may be confused with excess iron loss.

To overcome these disadvantages, the "wound-rotor" method may be used. This method consists of providing a winding on the test rotor and exciting from the rotor instead of the stator. Tests may then be made on bare cores without any windings, housing, or any machining whatsoever, thus eliminating any question of defective windings when iron loss is being investigated or controlled. Also progressive tests may be made after each winding and machining operations to see if any harm has been done to the magnetic structure and increased the iron loss.

The same differences occur between the condition of actual operation and the condition of wound-rotor test as occur with the dummy rotor. That is, the flux in the rotor is at line frequency instead of slip frequency, and the flux distribution may be less sinusoidal than in the actual machine with squirrel-cage rotor. If the wound rotor is designed for this purpose, it can have sinusoidally distributed windings which will keep this difference fairly small. The main difference in the flux distribution of the wound rotor is that the excitation comes from the rotor. This means that the gradual loss of leakage flux from the useful flux progresses from rotor to stator instead of from stator to rotor. To be specific, in the regular case the air-gap flux is less than the stator flux by the leakage but in the wound-rotor test, the air-gap flux must be kept greater than the stator flux by the leakage in order to give the same stator flux; actually the matter can be easily taken care of by adjusting the turns of the rotor, and except for extremely high densities the difference in flux distribution does no harm.

Wound rotors are usually made single phase to eliminate the error of two large wattmeter readings which occurs on the two-wattmeter method with three phase.

It is usually necessary to deduct the rotor copper loss when comparing iron-loss readings, particularly if some of the stator cores are ground to finished diameter and some are as punched. In order to obtain a better representation of percentage differences, the rotor iron loss also may be deducted. The value may be obtained by calculation or by test with a special oversize dummy stator, bored to size, but having no slots and a diameter much bigger than the regular stator. The densities in this will be very small, and even a rough calculation is sufficient to determine the iron loss. To be more specific, a test is made of the wound rotor in the dummy stator. The rotor copper loss and calculated stator iron loss are subtracted from the input. The remainder is used as the rotor iron loss for all further testing with the wound rotor.

For some work it is desirable to keep all conditions of the wound-rotor tests as near like actual conditions as possible. In these cases, the same number of poles are used as in the motor windings. However, many times the readings are magnified and more useful when two-pole rotors are used.

As in the case of the dummy rotors, high frequency may be used to make the tests more sensitive.

Table I. Regular Test of Stator Cores

Volts = 91

	Stator Number					
	1		2		3	
	Max	Min	Max	Min	Max	Min
Amperes	2.13	1.82	2.08	1.82	2.13	1.92
Watts	24.0	22.0	25.5	24.5	23.0	22.0
Resistance after test	1.410		1.410		1.410	
I^2R	6.4	4.7	6.1	4.7	6.4	5.2
Total iron loss	17.6	17.3	19.4	19.8	16.6	16.6
Total iron loss from item 1	5.5	5.5	5.5	5.5	5.5	5.5
Stator iron loss	12.1	11.8	13.9	14.3	11.1	11.3

It is often necessary to turn the wound rotor in the stator being tested and take maximum and minimum readings. The effect of the grain of rolling the steel, and the effect of rivet and bolt holes are often quite pronounced.

Very often the need of a wound rotor for test analysis or trouble shooting occurs without warning, and there is no time to design and build a special rotor. Sometimes in these cases, a d-c or repulsion-motor armature may be obtained and leads soldered to opposite commutator bars for connections. Even if the air gap is larger than desirable or unusual test voltage and frequency necessary, comparative readings usually can be obtained which are usable in separating good and bad stator cores.

If wound rotors are used continuously, the windings and core structure are apt to become damaged. Protective coatings of varnish or other material should be used. Sometimes it is desirable to have a master standard kept in the laboratory for calibrating new or rewound rotors.

Wound rotors may be used as turn counters for stator windings by reading the induced voltage in the maximum position. If the test is a routine one comparing production stators with a master or sample stator, a direct reading is sufficient. If turns of an unknown winding are desired, it is necessary to apply voltage and read induced voltage on both rotor and stator. In this case

$$K = \frac{\text{effective turns of stator}}{\text{effective turns of rotor}} = \sqrt{\frac{E_s \text{ read}}{E_s \text{ applied}} \times \frac{E_s \text{ applied}}{E_r \text{ read}}}$$

Very often stator short circuits can be distinguished from excessive iron loss by turning the wound rotor. Usually stator short circuits are of a single-phase nature such as one turn or one coil short-circuited. In this case, the maximum reading shows up the short circuit very prominently, and the minimum reading shows no effect at all.

A typical example of the use of wound and dummy rotors occurred some years ago. The first indication of trouble was an excessive number of rejects on final motor test. After a number of the

Power Systems for Auxiliary Drives in Steam-Electric Stations

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A STEAM-ELECTRIC power station in general consists not only of such major items as boiler equipment, steam-turbine-generator units and condensers, but also of many auxiliaries. These auxiliaries now have come to be almost exclusively a-c-motor-driven, although steam-driven auxiliaries are used occasionally in some topping installations where their use improves the heat cycle and in other cases for stand-by service. Since the reliability of a station can be no better than the reliability of its auxiliaries, the power-supply system for these auxiliaries, as well as the associated motors and control, become important items in the design of a steam-electric-power station.

These considerations in conjunction with the recent rapid rise in the quality and acceptance of factory-assembled switchgear, control, and transformer equipments make it now opportune to consider the design of the power system for these auxiliaries, taking full advantage of factory-assembled equipments. It is hoped that this discussion will not only direct proper attention to this over-all problem, but also indicate how a new level of reliability, economy, simplicity both in installation and operation, and safety to personnel can be obtained readily on power systems for auxiliaries by proper design approach based on such factory-assembled equipments.

As a result of discussions with several operating groups and after studying various types of auxiliary-power systems, together with the existing methods of obtaining auxiliary power, the following general conclusions have been reached. These conclusions should serve as a guide in planning power systems for auxiliaries.

Conclusions

1. A separate auxiliary-power system should be considered for each boiler.
2. Power supply from the main-generator leads is being increasingly used.
3. The preferred voltages are 460 and 2,400 volts.
4. It is economical to use a single-voltage 460-volt system, where the required transformer capacity per boiler does not exceed 1,000 kva.
5. A dual-voltage system comprising 2,400 and 460 volts should be considered where the required transformer capacity per boiler is 1,500 kva or greater.
6. In a dual-voltage system motors up to at least 250 horsepower can be economically applied at 460 volts.

Power Requirement of the Auxiliaries

The over-all auxiliary-power requirements for any given new steam-turbine-generator capacity can never be determined precisely until the plant is placed in operation. However, it can be reasonably estimated if proper attention is given to such details as the number and type of boilers, the pressure and maximum flow of steam, the nature of the feed-water piping, and the type and treatment of fuel. This last item is particularly significant, as it is evident that pulverized-coal-fired boilers will require more auxiliary power than boilers using other types of fuel, because of the pulverizers and exhauster fans.

Figure 1 gives the approximate total auxiliary power in per cent of the maximum output of a turbine-generator set. In addition, the probable individual power requirements for the major auxiliaries are indicated. The auxiliary-power requirement should be based upon the actual maximum output of the turbine-generator set. In a specific case this output may be any value between the nominal rated and the maximum permissible from the set, depending upon the capacity of the boiler plant. Thus, since the boiler capacity is selected normally with a margin to cover adverse conditions of fuel, draft, and boiler maintenance, it is evident that the boiler-plant capacity really determines the auxiliary-power requirements, through its effect on the actual maximum output of the set.

The total auxiliary power, of course, is the difference between the gross and net output of the turbine-generator set. The total auxiliary transformer capacity can be approximated by assuming a power factor of 0.8 to 0.85 for the power requirements obtained from Figure 1. In the final design, however, transformer capacities should be determined conservatively by totalizing the coincidental loads with due regard for power factor. In addition, provision must be made for general station power facilities such as lighting, machine shop, and coal-handling equipment. These general station power requirements are very often associated with the auxiliary-power supply for the first one or two units in a station.

The size of the individual motors for the major auxiliaries is determined largely by the rating of the individual boilers and

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good and bad motors were tested by the dummy-rotor method, it became certain that the trouble was in the stator and was due either to short circuits or excessive iron loss. Resistances and torques indicated that the number of turns were probably correct.

After the good and bad stators were tested by the wound-rotor method, it was found that the bad stators were bad in both maximum and minimum positions. This created considerable suspicion of short circuits in the stator windings. This point was settled when the stators were stripped. The good stators remained good, and the bad stators remained bad, with the readings the same as before the windings were removed.

This was considerable relief to the winding department which had previously been rewinding so called "defective" stators.

The next step was to institute a 100-per-cent wound-rotor test on all stator cores before winding. This immediately removed the rejects.

Upon further investigation of the good and bad cores as they came from the core building department, the trouble was found to be due to a lack of insulating iron-oxide scale which was the only insulation between individual laminations. Once this condition was corrected, and proper insulation provided between laminations, the rejects of defective cores prior to winding dropped to practically zero and the 100-per-cent core test was taken off.

Appendix. Typical Test and Analysis

1. Wound rotor tested with dummy stator to determine rotor iron loss:

Volts = 91
Amperes = 0.64
Watts = 8.30
Resistance after test = 1.406
$I^2R = 0.58$
Total iron loss = 7.72
Calculated stator iron loss = 2.22
Rotor iron loss = 5.50

2. The regular test of stator cores is shown in Table I.

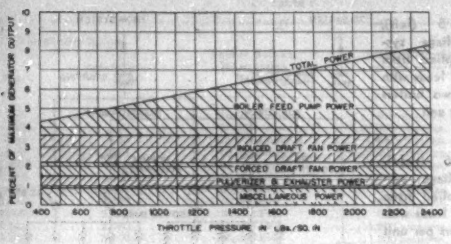


Figure 1 (left). Approximate total auxiliary power in per cent of maximum generator output in kilowatts and approximate division of power between major auxiliaries

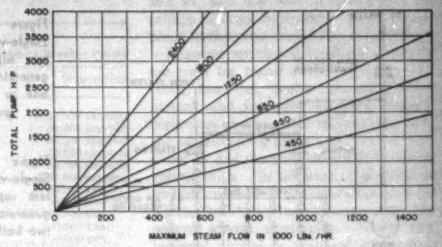


Figure 2 (right). Boiler-feed-pump power for various pressures and maximum steam flows

does not necessarily bear any direct relation to the size of the turbine-generator set or the total auxiliary power associated with that set. As an aid in estimating the probable boiler arrangement for any contemplated installation, present boiler practice may be broadly summarized as follows:

Steam-turbine-generator units up to approximately 30,000 kw maximum rating generally have a single boiler; units between 30,000 kw and 60,000 kw maximum rating may have either one or two boilers, and practice is about equally divided in this region; units above 60,000 kw maximum rating generally have two boilers, although single boilers are now available and occasionally used up to a capacity of 1,000,000 pounds of steam per hour.

Boilers are usually rated in pounds of steam per hour, and a reasonable average steam rate for modern turbine-generator sets is nine pounds of steam per kilowatt-hour. Thus, it is evident that a 1,000,000-pound boiler would supply steam for a set output of at least 110,000 kw.

Figure 2 shows the estimated boiler feed-pump power for various pressures and flows, including liberal allowance for head loss in piping. In the smaller plants it is the usual practice to have a minimum of two pumps, each large enough to deliver maximum flow. This results in at least 100-per-cent spare pump capacity. In the larger plants two pumps often are required to provide maximum flow, and a third serves to provide 50-per-cent spare capacity. In some of the larger plants, boiler feed-water supply is provided by a combination of tank and booster pumps in series. In such arrangements, the booster pump is usually variable speed and of sufficient capacity to give the required outlet pressure range for the particular plant conditions and at the same time offset the rising pressure characteristic of the constant-speed pump at the lower flows. The capacity of such a combination may vary from 50 to 100 per cent of the total boiler requirements.

The actual motor ratings, in most cases, will be slightly greater than the values derived from Figure 2.

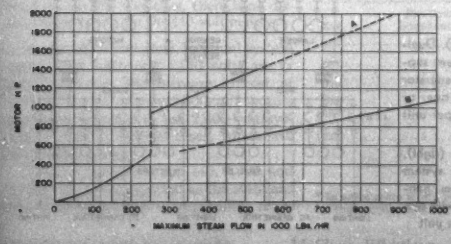
Figures 3 and 4 show approximate motor ratings for induced-draft and forced-draft fans, respectively. These curves are based on average values obtained by plotting actual motor ratings for several boiler ratings. The discontinuity between 200,000 pounds and 300,000 pounds flow results from a change in boiler construction in this region. It will be noted that induced-draft fans require more power than forced-draft fans. Thus, in practice, as the size of a boiler increases, two induced-draft fans often will be used with one forced-draft fan. Finally, in the largest boilers, both induced- and forced-draft fans may be split into two groups.

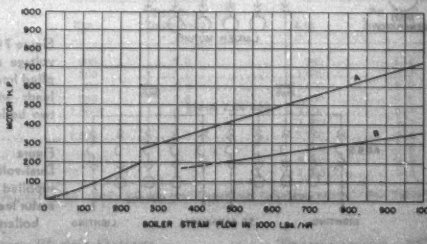
Figure 3 (left). Induced-draft-fan power

A—One fan per boiler or total power
B—Two fans per boiler—power per fan

Figure 4 (right). Forced-draft-fan power

A—One fan per boiler or total power
B—Two fans per boiler—power per fan





Power System Application Guides

A power-supply system for auxiliary drives in a steam-electric station is unique in many respects, for example:

1. There are a few large motors.
2. There are many small motors.
3. The cable runs are short.
4. The load is relatively constant.
5. Voltage regulation is very seldom a problem.

In planning a system the following principles and practices which have demonstrated their soundness in service should be recognized:

(*a*). An adequate source of power must be available for starting up the plant.

(*b*). The entire system should be considered essential, since the essential motors are both large and small and are not confined to any one location in the plant.

(*c*). In cases where two voltages are used, it simplifies operation and switching arrangements to bring all the power to the higher-voltage bus.

(*d*). The reliability of metal-clad, insulated five-kilovolt busses and metal-enclosed 600-volt busses justifies a single-bus system.

(*e*). The reliability of power transformers justifies the use of a conventional radial system.

(*f*). High short-circuit currents should be avoided.

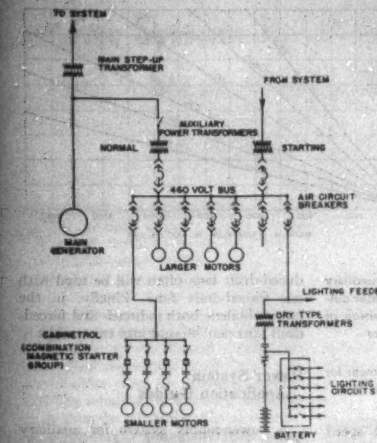


Figure 5 (left). Single-voltage system supplied from generator leads with one or two boilers per unit

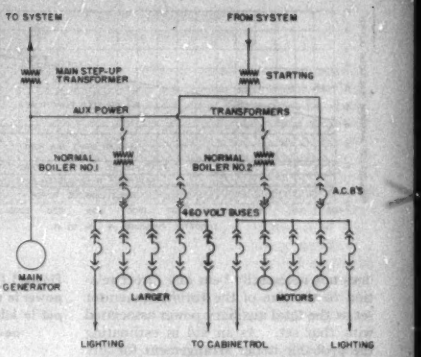


Figure 6 (right). Single-voltage system supplied from generator leads with two boilers per unit

The Auxiliary Power Source

Auxiliary power may be obtained from any of the following sources:

(*a*). Main-generator leads.
(*b*). Generator bus.
(*c*). House turbine-gencrator set.
(*d*). Direct-driven shaft generator.

The choice among the afore-mentioned sources of power is frequently based upon opinion which may in turn be founded upon some annoying experience. When a shaft generator or house turbine-generator set is used, the performance of the auxiliary-power system is not affected by disturbances on the main system. So far as efficiency is concerned, the house turbine-generator set is at a disadvantage because of the inherent lower efficiency of the smaller turbines. In cases where either type of auxiliary generator is used, there are the disadvantages of the resultant added cost and complexity.

In addition there are such detailed difficulties as starting large motors from a relatively small generator, and the possible troubles with paralleling main and auxiliary generators and transferring from the starting power source to the separate generator. Auxiliary generators used in these applications are usually of the high-speed turbine-generator type, and, when equipped with an automatic voltage regulator, a motor with a rating up to one-third that of the generator generally can be started acceptably. A more severe voltage condition may occur after the transfer of a large group of motors from a starting source to an auxiliary generator, resulting from the increased reactive motor currents at the reduced motor speeds.

Auxiliary Power From Generator Leads

There seems to be, however, an increasing trend toward the unit system and with it an increased tendency to obtain power directly from the leads of the main generator. So far as cost and simplicity are concerned, this method has definite advantages. This provides auxiliary power at the efficiency of the main set and permits the unit to go back into service immediately after having been tripped off as a result of a system disturbance. Practice indicates that the short length of cable plus the auxiliary transformer connected to the leads of the main generator very seldom is responsible for an outage of the unit. Of course, a starting source of power is required, but one such source

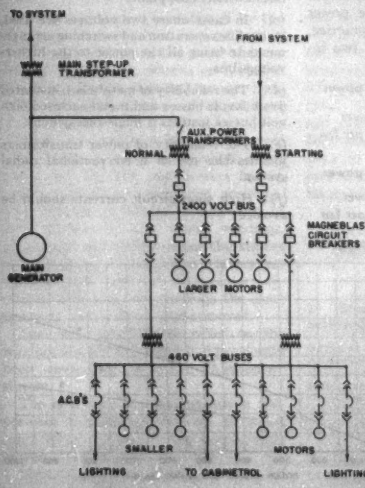


Figure 7 (left). Dual-voltage system supplied from generator leads with one or two boilers per unit

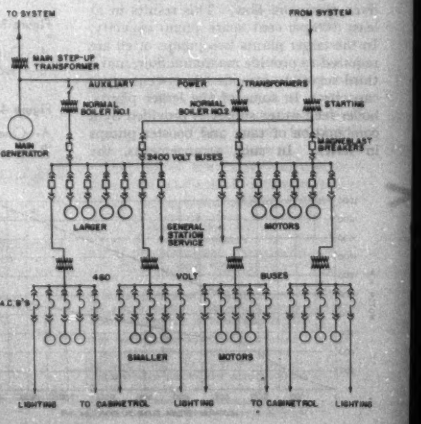


Figure 8 (right). Dual-voltage system supplied from generator leads with two boilers per unit

Table I

Transformer Rating		Feeder Breaker	Transformer-Secondary Breaker Rating	
Kva	Secondary Voltage	Interrupting Rating	Current	Interrupting
300	480	15,000 amperes	800 amperes	50,000 amperes
500	480	25,000 amperes	800 amperes	50,000 amperes
750	480	25,000 amperes	1,600 amperes	50,000 amperes
1,000	480	50,000 amperes	2,000 amperes	75,000 amperes
1,000*	480	25,000 amperes	1,600 amperes	50,000 amperes
1,500	480	50,000 amperes	4,000 amperes	100,000 amperes
1,500	2,400	50,000 kva	600 amperes	50,000 kva
2,000	2,400	50,000 kva	800 amperes	50,000 kva
2,500	2,400	50,000 kva	600 amperes	50,000 kva
3,000	2,400	100,000 kva	1,200 amperes	100,000 kva
3,750	2,400	100,000 kva	1,200 amperes	100,000 kva
5,000	2,400	100,000 kva	1,200 amperes	100,000 kva

* It will be noted that one transformer rating, 1,000 kva at 480 volts, has an impedance higher than the generally accepted standard. This permits the use of feeder breakers having a lower-than-normal interrupting rating for this transformer size and results in a more economical installation in spite of the special transformer. It will be found that attempting to use special impedance values for smaller transformer ratings at 480 volts will result in only a minor saving in equipment cost and a small reduction in fault currents which are already considered acceptable. In the case of larger transformers at 480 volts, the high impedance required to permit the use of lower breaker ratings results in both impractical transformer design and excessive voltage regulation.

will suffice for several unit busses. When the supply is through a transformer, the voltage dip incident to motor starting is seldom a problem.

The Auxiliary-Power Voltage

In laying out an auxiliary-power-supply system, there are two voltage classes of equipment to be considered, namely, 600 volt and 5,000 volt. The cost of cable and control equipment in any voltage class is dependent largely upon its current rating. Thus, unless there are other offsetting factors, equipment and apparatus should be used at as high a voltage rating in its class as is practical.

In the 600-volt class, nominal system voltages of 115, 230, 460, and 575 volts have been used. In this discussion 460 volts is considered throughout as the preferred level in the 600-volt class for the following reasons:

1. The 460-volt system is considered to be the conservatively high voltage in this class.

2. Motors and control at this voltage are widely used and therefore readily available.

3. At 440 volts practical motor ratings are large enough to overlap the lower practical motor ratings for both 2,300 volts and 4,000 volts.

4. At 440 volts practical motor ratings include those down to one-half horsepower and thus overlap the higher practical ratings of single-phase 120-volt motors.

5. Since motor prices are the same for all levels in the 600-volt class, there is no disadvantage in cost for the 440-volt motors.

In the 5,000-volt class, nominal system voltages of 2,400 and 4,160 volts are in use. However, the increase in cost of 4,000-volt motors over 2,300-volt motors makes it desirable to use 2,400-volt systems, except in special cases, which will be discussed later.

Thus, in this discussion 440, 2,300, and 4,000 volts are recognized as the standard motor voltages, with corresponding nominal bus voltages of 460, 2,400 and 4,160 volts, respectively. To insure 460 volts at the bus a transformer secondary voltage of 480 is normally used. At the two higher voltages transformer secondary voltages are usually the same as the bus voltages, in view of the short cable runs encountered.

600-Volt Equipments

There are various types of control for low-voltage a-c motors, all of which include means for starting and stopping the motors, and also for providing any combination of motor overload and short-circuit protection. These types may be grouped as follows:

(*a*). Combination magnetic starters, using thermal air circuit breakers for short-circuit protection. These are available in sizes up to and including size-V starters.

(*b*). Combination magnetic starters, using fusible disconnects for short-circuit protection. These are available in sizes up to and including size-III starters.

(*c*). Drawout electrically operated air circuit breakers, which are available in all ratings of the breakers.

The specific ratings of the foregoing equipments are shown later in Tables V and VI, and it should be noted that all ratings of these equipments may be combined in the same respective assembly.

Drawout air circuit breakers generally are used for transformer secondary circuits, bus ties, feeder circuits, larger motors, and for most essential motors, regardless of size. The air breakers have the advantage of being a latched-in type of device and therefore do not drop out on voltage dips. In addition, the drawout feature provides disconnecting means which facilitates maintenance and improves service continuity. Their use, however, should be confined to applications where the required number of operations is not excessive.

Combination magnetic starters are used customarily for the smaller motors and also on applications where repetitive starting conditions are encountered. They can be furnished in factory-assembled, metal-enclosed groups, known as Cabinetrols. In general, it also will be found that drawout air circuit breakers will be less expensive than size-IV or larger combination starters, whereas combination starters will be less expensive up to and including size III.

Electrically operated drawout air circuit breakers for this type of service are furnished in metal-enclosed groups and referred to as drawout-air-circuit-breaker equipments.

5,000-Volt Equipments

There are two arrangements available for controlling high-voltage a-c motors, both of which provide combination short-circuit and overload protection:

(*a*). Metal-enclosed high-voltage contactors with current-limiting fuses.

(*b*). Vertical-lift metal-clad switchgear, with Magneblast circuit breakers.

The complete ratings of these equipments are given later in tables.

The fused starters are available for motors up to 700 horsepower at 2,300 volts. Fuses will, in general, clear a short-circuit more rapidly than the breaker. The contactors have long mechanical life and are best applied where a large number of operations will be encountered. From

Table II

2,400–480 Volts		13,200–480 Volts		13,200–2,400 Volts	
Kva	Per Cent Impedance	Kva	Per Cent Impedance	Kva	Per Cent Impedance
200	5.0	200	5.0	750	5.5
300	5.0	300	5.0	1,000	5.5
500	5.0	500	5.0	1,500	5.5
750	5.5	750	5.5	2,000	5.5
1,000*	5.5	1,000*	5.5	2,500	5.5
				3,000	5.5
1,500	5.5	1,500	5.5	3,750	5.5
				5,000	5.5
				6,000	5.5
				7,500	5.5

* In some cases it will be advantageous to specify 8.0 per cent impedance for these ratings. See Table I for their application.

a cost standpoint 50,000-kva metal-clad switchgear and fused starters are about equal, while for the higher interrupting ratings the first cost of fused starters is less.

On the other hand, when fuses are applied, there is always the possibility of single-phase motor operation due to the blowing of one fuse. Also, most large motors for station auxiliary drives do not require frequent starting and stopping. Further, most installations of this size will have one or more motors larger than 700 horsepower. It has thus been general practice to use circuit breakers for controlling the larger motors, and in the transformer, bus tie, and feeder circuits.

Transformers

Three-phase transformers are used almost exclusively in both the single- and dual-voltage auxiliary-power systems. Oil-filled or Pyranol-filled transformers for outdoor use and Pyranol-filled or dry-type transformers for indoor use are available. Transformers having ratings and characteristics as indicated in Table II may be obtained and are regularly provided with manually adjustable taps.

Unit Substations

The metal-clad switchgear equipments, using vertical-lift Magneblast breakers, and their transformers are available in unit equipments as shown in Figure 10 and are known as master unit substations.

The metal-enclosed drawout-air-circuit-breaker equipments and their transformers are generally furnished in unit equipments as shown in Figure 11 and are known as load-center unit substations. Cabinetrol equipments and transformers also can be furnished in unit equipments known as Cabinetrol unit substations.

Power-System Arrangements

Figures 5 to 9 suggest several auxiliary-power-system arrangements, and there are obviously many more which could be shown. Most of these arrangements show the auxiliary power coming from the main-generator leads primarily because of its increased use.

Figure 5 applies to a plant with one or two boilers, where all the auxiliary power may be properly supplied at 460 volts. Individual feeder positions control the larger motors, and others supply one or more lighting circuits, as well as one or more groups of magnetic starters which control the smaller individual motors. Transformer secondary breakers are used so that transfer from the starting to running supply may be readily made. Interrupter switches, where shown, permit isolating the transformers for maintenance purposes.

Figure 6 applies particularly for a small unit having two boilers in which the auxiliary power is split into a supply for each boiler. This arrangement reduces the short-circuit duty on the low-voltage busses and prevents outages on one boiler system from involving the other boiler's system. One transformer is shown as a starting supply for either bus, but a separate starting transformer for each bus will give complete reserve capacity.

Figure 7 applies to plants using either one or two boilers, where the amount of auxiliary power is sufficient to justify the use of two voltages. The high-voltage transformer-interrupter switches and secondary breakers at 2,400 volts serve functions similar to those indicated on Figure 5. The larger motors are supplied at 2,400 volts, and one or more 2,400-volt feeder positions supply transformers which step down a portion of the total power to 460 volts. Bus ties are not shown between the 460-volt busses, and thus transformer secondary breakers are not required at 460 volts. When reserve transformer capacity to the 460-volt busses is considered desirable, transformer-secondary and bus-tie breakers may be added. In order to keep within the interrupting rating of the 600-volt air circuit breakers it is sometimes advantageous to supply two or more transformers from one 2,400-volt feeder. If bus-tie breakers are used in this arrangement, they should be used between 460-volt busses which are fed from different 2,400-volt feeders.

Figure 8 applies particularly for the larger units having two boilers. Dividing the power into a supply for each boiler reduces short-circuit duties and prevents outages on one boiler system from involving the other boiler's system. One transformer is shown as a starting supply for either 2,400-volt bus, but one for each bus would give 100 per cent reserve capacity.

Figure 9 shows how a power supply for auxiliaries can be taken directly from the low-voltage station bus when such a bus is available.

Table III

Interrupting Rating in Kva	Ampere Rating
50,000	600
	1,200
100,000	600
	1,200
	2,000
150,000	600
	1,200
	2,000

Table IV

Voltage	Interrupting Rating—Kva	Horsepower Rating
2,400	150,000	50–700
4,160	250,000	50–1,250

Table V

Interrupting Amperes	Continuous Ampere Rating	Maximum Motor Horsepower at 440 Volts	Maximum* Setting of Instantaneous Trip—Amperes
15,000	15–225	150	3,375
25,000	15–225	150	3,375
25,000	250–400	275	6,000
25,000	450–600	400	9,000
50,000	100–225	150	3,375
50,000	250–600	400	9,000
50,000	800–1,200	800	18,000
50,000	1,600		24,000
75,000	2,000–2,500		30,000
75,000	3,000		36,000
100,000	4,000		48,000

* The maximum setting of the nonadjustable instantaneous short-circuit trip on the air circuit breakers is important in determining the rating of the transformer-secondary breaker, so that it will not trip for feeder faults.

For the larger stations, it may be desirable to establish a separate centrally located bus from which the general station service power is distributed. The so-called starting transformer can then be used to bring power from the system to this bus which in turn can also be arranged to provide starting power for the individual unit busses.

Single-Voltage Systems

Studies show that, so far as investment is concerned, on the basis of the typical number of feeder positions usually required by the smaller turbine-generator units, the straight 460-volt system and the 2,400–460 dual-voltage system are practically equal when the normal power supply demands a 1,500-kva transformer. Below this rating there is a definite cost advantage in favor of the straight 460-volt system. In fact, if the auxiliary power supply can be held within the capacity of a 1,000-kva transformer, the short-circuit duty on such a 460-volt auxiliary system will be limited accordingly, and the 440-volt motors and control for the larger auxiliaries associated with this amount of total auxiliary power, will not result in an impractical solution.

Dual-Voltage Systems

As previously indicated, studies show that a dual-voltage system should be considered when the auxiliary-power supply requires a 1,500-kva or larger transformer. In most of these applications, 2,400 volts will be more economical than 4,160 volts. Actually transformer capacities up to and including 5,000 kva at 2,400 volts may be used with economical and practical switch gear having an interrupting rating of 100,000 kva.

A 5,000-kva transformer will supply power to a boiler having a flow of approximately 600,000 pounds per hour. Boilers larger than this are most always provided with split auxiliaries such as two induced-

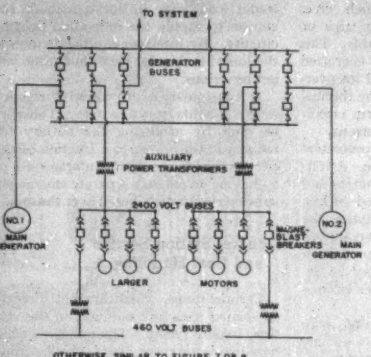


Figure 9. Dual-voltage system supplied from generator bus

draft fans, two forced-draft fans, and two or more boiler-feed pumps. So far as auxiliaries are concerned, such a boiler has the advantages of a two boiler installation, and the 2,400-volt auxiliary power may be divided as shown in Figure 8. Thus, by using divided auxiliaries and two auxiliary-power transformers rated either 3,750 or 5,000 kva, the power for most of the largest boilers may economically be supplied at 2,400 volts.

For the larger installations, where individual transformer ratings greater than 5,000 kva may be required, the use of 4,160 volts should be considered. Systems using 4,160 volts have the advantage of lower-current ratings and lower short-circuit currents but may not necessarily show an advantage in cost owing to the higher cost of 4,160-volt motors. Whatever the relative economics of the motors and control are, it should be recognized that raising the voltage always reduces the short-circuit amperes, and thus at 4,160 volts the kilovolt-ampere capacity of the supply transformer can be larger than at 2,300 volts.

In the case of 2,400–460 dual-voltage systems, studies indicate that, by evaluation of such cost items as difference in control equipment, cable, motors, and additional transformer capacity including evaluation of losses, it is economical for the short runs normally encountered in a steam station to include motors up to 250 horsepower in the 460-volt class. Similarly, in the case of 4,160–460 dual-voltage systems, it is generally economical to include motors up to 350 horsepower in the 460-volt class.

It will be seen from Figure 1 that in the normal auxiliary-power system the few motors associated with the larger auxiliaries account for two thirds to three quarters of the total auxiliary power. Thus, when a complete list of the motors and their ratings is available, there should be little difficulty in selecting not only the motors which are to be supplied at 460 volts but also the total transformer capacity required to serve these motors.

In plants where medium-size boilers are used, this one third of the total kilovolt-ampere is often stepped down from 2,400 volts to 460 volts through one transformer on a radial basis. Where larger boilers are employed, two or more transformers may be used on a radial basis to step down power from the 2,400-volt bus. This has the advantage of permitting the use of control equipment of lower interrupting rating and of allowing the control to be located nearer individual groups of motors.

When a strictly radial system is not considered adequate, the first departure will consist usually of adding a tie breaker between 460-volt busses. In order to take full advantage of this feature; excess transformer capacity must be provided. The magnitude of this excess capacity admittedly is a matter of judgment, however, and 50-per-cent excess capacity should be sufficient in most cases. Provision should be made to prevent closing the bus-tie breaker between any pair of busses unless one of the two source breakers is open, or at least will be opened promptly after the bus-tie breaker is closed.

In a plant with two boilers per generating unit, with a separate auxiliary-power supply for each boiler, it will simplify operation to adhere strictly to the unit-system concept in the auxiliary-power supply and thus avoid such complications as providing bus ties between 460-volt busses which normally supply auxiliaries for different boilers.

Relaying Selectivity

For essential types of service such as power-station auxiliary drives, selective operation of feeder breakers and transformer-secondary breakers is desirable during fault conditions on the feeders. When a transformer-secondary, bus-tie, or group feeder breaker is to be selective with the feeder breakers it must not trip instantaneously. In this way the feeder breaker is given an opportunity to trip and clear the fault, and therefore it must have an interrupting capacity at least equal to the available fault. Low-voltage air circuit breakers are all equipped with instantaneous trips, and thus any of these breakers in backup positions must be of sufficient rating so that their instantaneous trips will not cause breaker operation on feeder faults.

Power circuit breakers on motor circuits usually are equipped with instantaneous over-current relays for fault protection; thus, the breakers in backup positions may be timed to be selective with respect to motor breakers and other feeder breakers.

Table I summarizes the present breaker ratings which can be used with the transformer ratings listed in Table II and can be expected to give selective operation of 600-volt air circuit breakers during short-circuit conditions. The maximum setting of the nonadjustable instantaneous short-circuit trip on low-voltage air breakers is given in Table V. For convenience the ratings of 5,000-volt breakers for larger transformers also are included in Table I. The higher system short-circuit duties, encountered in this type of service, have been used in selecting these ratings.

Cabinetrol equipments as normally applied are not selective with the group feeder breakers over a wide range of ratings. This will not be serious if all essential motors, regardless of how small they may be, are supplied from their individual 600-volt air circuit breakers. In some cases, small essential motors will require contactors because of the frequency of operation of their control. If such auxiliaries are in duplicate, they may be supplied from two different Cabinetrol groups and in this way still meet the service reliability requirements.

Selectivity of Cabinetrol as normally applied may be expected with certain com-

Table VI

NEMA Size	Interrupting Element	Interrupting Rating—Amperes	Maximum Horsepower at 440 Volts
1	Fuse*	50,000	7½
2	Fuse*	50,000	25
3	Fuse*	50,000	50
1	Thermal air circuit breakers†	15,000	7½
2		15,000	25
3		15,000	50
4		15,000	100
5	Air circuit breaker	25,000	300

*The fusible-combination magnetic starters, when equipped with nonrenewable nonindicating National Electric Code fuses, are adequate for installing in circuits where the available symmetrical short-circuit current at the incoming-line terminals of the starter does not exceed 50,000 amperes and the short-circuit is at or beyond the load terminals of the starter.

† Where these combination magnetic starters with thermal air circuit breakers are supplied through a 25,000-ampere 460-volt air circuit breaker, the starters may be applied on a bus having an available short-circuit duty of 25,000 amperes.

bination ratings. Fused Cabinetrol equipment at 460 volts up to and including size II will, in general, be selective with a 25,000-ampere group feeder breaker. For larger-fused Cabinetrol units and for all Cabinetrol units using thermal air breakers, a 25,000-ampere group feeder breaker can be expected to trip during a short-circuit.

However, when selectivity of Cabinetrol in a wider range of ratings is desirable, it may be obtained either by choosing a group feeder breaker with a sufficiently high instantaneous setting or by using a series feeder reactor. Either of these approaches increases the spread between the available short-circuit current and the maximum instantaneous trip setting for the feeder breaker.

Protective Features

Instantaneous short-circuit protection is provided on all types of control equipment. Combination magnetic starters are equipped with either fuses or thermal air circuit breakers, and low-voltage air circuit breakers are equipped with instantaneous trips. Instantaneous overcurrent relays are also used on the Magneblast air breakers.

Inverse time-delay short-circuit protection should be normally provided as backup protection on transformer-secondary, bus-tie, and transformer-feeder circuit breakers. When these breakers are of the 600-volt type, this feature preferably should be obtained by using separate relays with current transformers. On Magneblast breakers separate relays must be used.

Thermal devices are available in all the types of equipments discussed, and their function is to provide inexpensive overcurrent protection for motors against stalled rotor and single-phase operation or prolonged overloads. They may be arranged either to trip the motor circuit or to sound an alarm, and the opinions of operators are not uniform on this subject.

When the thermal device is arranged for tripping, it opens the coil circuit on magnetic starters; it acts directly on the trip element of low-voltage air circuit breakers and on the larger breakers is used in conjunction with current transformers to energize the breaker shunt trip coil. In applications where a special thermal characteristic must be met, a separate thermal relay, energized from current transformers can be used to provide the trip function on any of the equipments.

When alarm features only are desired, the thermal devices in all the equipments discussed can be arranged to sound an alarm instead of opening the motor circuit. Since an alarm is of no use except where there is time to profit by it, this feature is of advantage only during overloads and not during stalled rotor conditions and probably may be tolerable only on the smaller inexpensive motors.

A combination feature which gives alarm on overload and which trips on stalled rotor conditions is available. This consists of a thermal relay, energized from current transformers, and an overcurrent relay, which transfers the thermal relay from the alarm to the trip circuit upon the occurrence of excess current.

Undervoltage time-delay protective features are sometimes desirable. A voltage dip which drops out contactors and does not return to the required pickup value in a few seconds may damage the a-c operating coils of contactors equipped with undervoltage release, and protection against such a voltage dip may be arranged to trip any of the feeder circuits having devices of this type.

Differential protection of the main generator should be extended to include the normal auxiliary-power transformer. Generally, the ratios are not sufficient to allow the main differential relaying to detect faults in the auxiliary transformer;

Figure 10. Typical master unit substation

therefore an additional relay system should be provided for the auxiliary transformer to trip the generator breaker, field breaker, auxiliary-transformer-secondary breaker, and, in some cases, the turbine stop valve. In addition, automatic throwover may be provided to energize the auxiliary bus from the starting supply whenever differential relays trip off the main source. This allows the boiler to be brought down under full control of its auxiliaries.

It is common practice to operate 460-volt and 2,400-volt auxiliary-power systems ungrounded but with ground indication facilities.

Lighting

Station lighting can be economically taken from the 460-volt busses through one or more three-phase feeder positions. Single-phase dry-type transformers, of proper rating and number to balance the feeder load, may be located about the station to supply the individual lighting circuits. By interspersing these circuits, the loss of one feeder for a short time will not be serious.

It is customary to provide an emergency source of lights from a battery. This may be done by arranging the battery for automatic throwover to a fraction of the circuits which are again interspersed or by having an entirely separate emergency lighting circuit distributed over the area.

General Station Service and Coal Handling

Certain items, which are not directly associated with any one unit in the station, require power. These include coal-handling equipment, yard floodlighting, service water, machine shop, and cranes, and the amount of power required will vary widely for different plants. This power may be supplied from the auxiliary bus for the first unit in the plant, in which case provision should be made for an alternate source when additional units are added, or for the larger stations from a separate centrally located bus. It will be advantageous to supply this power from the higher auxiliary voltage since long cable runs are often involved.

Calculation of Short-Circuit Currents

In preparing the tabulated application guides, conventional methods of calculating short-circuit kilovoltamperes and currents were used.

The interrupting rating of Magneblast air circuit breakers is customarily given in kilovoltamperes at a certain voltage. The relay and interrupting times for these breakers are such that induction-motor contributions and offset currents may be neglected. Thus, the short-circuit kilovoltampere is determined directly from transformer reactance and system reactance beyond. In these applications the ratio of transformer reactance to system reactance is such that the system may as well be considered infinite. The momentary duty in these cases is obtained by multiplying the short-circuit kilovoltamperes by 1.4 and also adding the induction-motor contribution.

The interrupting rating of low-voltage air circuit breakers is the rms current averaged for the three phases and determined at the first half cycle, which is the time at which contacts part. This average value is determined by applying the multiplying factor of 1.25 to the symmetrical contribution through the transformer and then adding the contribution of induction- and synchronous-motor loads. The motor contribution is customarily taken into account by adding five times the connected motor load, which, in these applications, will be approximately

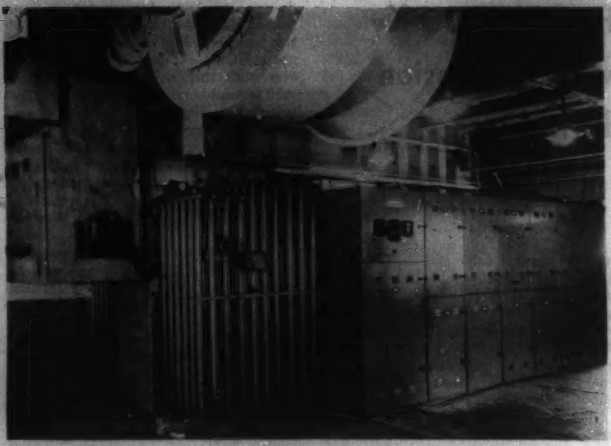


Figure 11. Typical load-center unit substation

five times the transformer rating. The momentary duty for this class of breaker is considered to be equal to the interrupting duty.

The interrupting rating of 600-volt fusible-combination magnetic starters is given in amperes based on the available symmetrical short-circuit amperes. This value may be obtained in a similar manner to that for low-voltage air circuit breakers, except omitting the 1.25 factor.

Location of Equipment

In steam-electric stations the major part of the power is used at or near the boiler. There is usually space available in the bay between the boiler plant and the turbine room where the auxiliary-power-system equipment can be advantageously located. This location should result in short power and control cable runs.

In the smaller plant where the power is supplied entirely at 460 volts, the complete switchgear and associated stepdown transformer may well be at one centralized location. The Cabinetrol may be at a remote location near a group of small motors which it serves.

In the larger plant where a dual-voltage system is used, the 2,400-volt switchgear logically should be at a central location in the plant. The 460-volt load-center units and Cabinetrol panels may be at remote locations near the load they serve. If the normal starting transformer is of moderate rating, consideration should be given to placing it at the centralized location, where it can be combined readily with the 2,400-volt switchgear into a unit substation. When the normal transformer is in the larger ratings, it will be located outdoors in most cases. Similarly, the starting transformer will be located outdoors, since it generally will be energized from the high-voltage bus, and in this way long high-voltage cable runs may be avoided.

Appendix

Transformer Ratings

Table II lists the standard transformer ratings which will be used normally for this type of service.

5,000-Volt Switchgear Equipments

Metal-clad switchgear, with electrically operated removable oilless circuit breakers, is available in the ratings shown in Table III.

Combination High-Voltage Fused Contactors

Metal-enclosed contactors with high-interrupting-current limiting fuses and with air or oil-filled contactors are available in the ratings shown in Table IV.

600-Volt Switchgear Equipments

Metal-enclosed low-voltage switchgear, with electrically operated drawout air circuit breakers have the ratings shown in Table V.

Combination 600-Volt Magnetic Starters

Combination magnetic starters with either fusible disconnects or thermal air circuit breakers are available for use as low-voltage motor starters. These starters are available in the ratings shown in Table VI.

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Study of Costs of 69- to 230-Kv Underground Power-Transmission Systems and Tie Lines

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Synopsis: This is a study of high-voltage underground-cable systems, consisting of the cable line and the terminal equipment at each of its ends. The study undertaken indicates the economic zone of application of cables and attempts to find an economic relationship between the voltage and the block of power transmitted over distances up to 15 miles. Thirty transmission lines have been designed using both the solid and the oil-filled cables. The lines can be considered as either transmission links with a unidirectional power flow or as tie lines between large metropolitan steam-power stations. The prices of underground cable and terminal equipment were obtained from manufacturers, and refer to the 12-month period immediately preceding World War II. The costs of various system parts, as installed on foundations, were obtained from the study of actual construction projects in different parts of the country and reduced to the 12-month period. The system capital cost and its annual cost are analyzed separately. The quantities of major equipment items in each system are given, and costs of major equipment groups, or of major items, are represented on a percentage basis. Such a representation permits the estimating of the cost of an underground line, or of the entire transmission project, when copper prices and the cost of equipment differ from those taken in the study.

THE RECORDS of engineering thought and development as reflected in the technical literature show that some 20 years ago there was displayed in the United States a great interest in the newly developed oil-filled cable. At that time 138-kv oil-filled cable was being installed in the United States and abroad. Since then extensive installations of this cable have been made, and the art has taken several steps forward—not only by developing an oil-filled cable for 230 kv but by evolving the gas-pressure cable and the Oilostatic system. The most notable installation of the 230-kv cable took place in France around the year 1936 when the intra-Paris cable 11.6 miles long was installed.[1–3] Cables of the newer type have also been placed in a few initial installations and may be considered as having amply justified their development.

The economic phase of underground transmission systems, however, did not receive during these years the attention given to the technical end of this problem. The only outstanding record in the literature is the study made by Roper[4] in 1931. In view of this, therefore, it seems that an economic study of this problem may be in order.

This study covers underground power-transmission and tie lines using impregnated-paper-insulated cables of the so-called solid and oil-filled types. Cables of other designs, such as the Oilostatic system in which the cables are installed in a pipe and maintained under a 200-lb.-per-square-inch oil pressure, or the high-pressure gas cables installed in a pipe or drawn into ducts, have not been considered, as at the time of preparation of this paper cost data on both systems were not available. It has been stated, however, that their over-all costs compare very favorably with those of an oil-filled system, showing costs in some cases smaller and in other cases slightly higher than those of an oil-filled system. It appears, therefore, that when a study is to be made of the cost of a projected underground power-transmission system consideration also must be given to these systems.

No attempt has been made to compare the economics of the underground and the overhead lines of equal length and equal

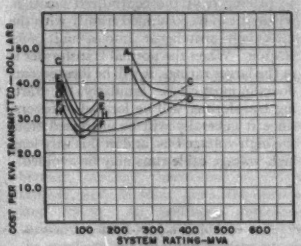

Figure 1. Capital cost of the entire system, including terminal substations, per kilovolt-ampere transmitted

A...15..230...Oil-filled cable
B...10..230...Oil-filled cable
C...15..138...Oil-filled cable
D...10..138...Oil-filled cable
E...15.. 69...Oil-filled cable
F...10.. 69...Oil-filled cable
G...15.. 69....Solid cable
H...10.. 69....Solid cable

The first figure represents transmission distance in miles; the second, kilovolts of transmission voltage

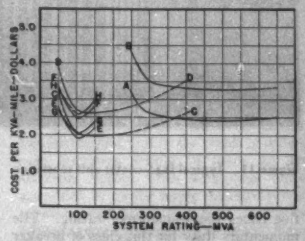

Figure 2. Capital cost of the entire system, including terminal substations, per kilovolt-ampere-mile

For explanation of identification letters, see Figure 1

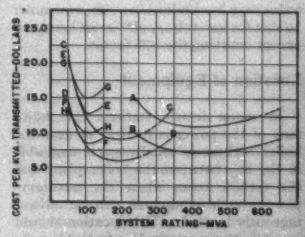

Figure 3. Capital cost of the transmission line per kilovolt-ampere transmitted

For explanation of identification letters, see Figure 1

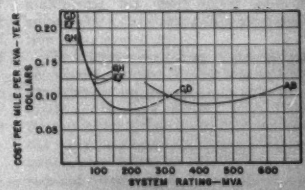

Figure 4. Capital cost of the transmission line per kilovolt-ampere-mile

For explanation of identification letters, see Figure 1

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To the engineers of the General Electric Company, the Westinghouse Electric Corporation, the General Cable Corporation, the Okonite Company, the Simplex Wire and Cable Company, and to several electrical-public-utility and consulting engineers the author expresses appreciation for valuable data and advice.

block of power transmitted. The systems differ from those studied by Roper in that in all cases they have terminal substations at both ends; they are studied and analyzed, however, both as complete systems with terminal equipment included, and as underground cable lines alone. The indirect expenses, which seem to have been purposely left out of Roper's study, are included in this paper. The general structure of the present study is similar to that used by the writer in his study of the costs of overhead power-transmission systems.[4] Therefore only an outline of the approach to the problem will be given here, and for a detailed method of analysis the reader is referred to similar parts of the other paper.

The underground systems investigated in this paper have no definite geographic location. The prices taken are those prevailing in the years preceding World War II. The prices of equipment are obtained from the manufacturers, and the cost of land, structures, substation secondary equipment, labor, and installation on foundation were obtained from various public-utility companies and from the literature. All these data were reduced to the common one-year period, with appropriate labor indexes being used. Irrespective of the variations in costs of particular items, the relationship between the costs of individual systems will remain basically unchanged. The study of the transmission of various blocks of power at two different voltages permits one to obtain the relationship of the voltage, the transmission distance, and the most economical block of power transmitted. It shows the general trend of high-voltage underground-system costs and defines the economic zone of application of the various cables studied.

The system capital and annual costs are calculated and analyzed separately.

System Description

The study covers 30 systems rated at 50,000 to 600,000 kva and transmitting power over one to four circuits of underground lines 10 and 15 miles long, at voltages of 69, 138 and 230 kv, at 60-cycle frequency. The systems are lines in metropolitan areas transmitting from steam-power stations, or lines tying in two great metropolitan load centers and permitting power to be transmitted in both directions. The transformer kilovolt-ampere capacity is assumed to be slightly greater at the sending end of the system.

The 69-kv cables are of both solid and oil-filled type, and all the 138-kv and 230-kv cables are oil filled, all cables being single-conductor cables. The underground lines are connected to high-voltage busses at both ends, and at no intermediate point are they connected to overhead transmission lines. Since the lines pass through metropolitan areas, there is no right-of-way problem, the assumption being made that permission to dig the trenches will be obtained from the municipalities.

The system and cable data are given in Table I.

The systems as taken in this study include the underground line, completed with all accessories, and the sending and the receiving substations. All systems have high-voltage busses and high-voltage circuit breakers at both ends of the system. All single-circuit systems have a single nonsplit high-voltage bus. The 149,700-kva-rated systems, with two circuits, have a single bus, split in two. For systems rated from 247,500 to 600,000 kva, double busses are provided; these busses are split into as many sections as there are circuits in the system. The load assumed on the system for the purpose of calculating the circuit-breaker interrupting capacity is at both system ends. The total load is the function of the block of power transmitted,[5] 60 per cent of the total being placed at the system receiving end, and the remaining 40 per cent at its sending end.

The underground lines have standard relay protection. Lines with solid cable

Table I. List of Systems Designed—Type and Size of Cables

System Identification Number	System Data: System Rating, Kva	System Data: Transmission Distance, Miles	System Data: Transmission Voltage, Kv	Cable Data: Type of Cable	Cable Data: Cross Section, Thousand Circular Mils	Cable Data: Number of Circuits in System	Cable Data: Cable Insulation Thickness, Inch	Cable Data: Thickness of Lead Sheath, Inch	Cable Data: Outside Diameter of Cable Over Lead Sheath, Inches
U-33*a*	51,200	10	69	Solid	600	1	0.656	0.125	2.452
U-331*a*	52,800	10	69	Oil-filled	350	1	0.315	0.125	1.790
U-34*a*	65,200	10	138	Oil-filled	168	1	0.560	0.141	2.165
U-35*a*	54,200	15	69	Solid	600	1	0.656	0.125	2.452
U-351*a*	52,800	15	69	Oil-filled	350	1	0.315	0.125	1.790
U-36*a*	65,200	15	138	Oil-filled	168	1	0.560	0.141	2.165
U-361*a*	75,300	10	69	Solid	1,000	1	0.656	0.125	2.872
U-362*a*	75,300	15	69	Solid	1,000	1	0.656	0.125	2.872
U-363*a*	76,900	10	69	Oil-filled	700	1	0.315	0.125	2.014
U-364*a*	76,900	15	69	Oil-filled	700	1	0.315	0.125	2.014
U-37*a*	103,600	10	69	Solid	1,750	1	0.656	0.125	3.482
U-371*a*	106,000	10	69	Oil-filled	1,250	1	0.315	0.125	2.300
U-38*a*	103,600	10	138	Oil-filled	400	1	0.560	0.141	2.342
U-39*a*	103,600	15	69	Solid	1,750	1	0.656	0.125	3.482
U-391*a*	106,000	15	69	Oil-filled	1,250	1	0.315	0.125	2.300
U-40*a*	103,600	15	138	Oil-filled	400	1	0.560	0.141	2.342
U-401*a*	149,700	10	69	Solid	1,250	2	0.656	0.125	3.052
U-402*a*	149,700	15	69	Solid	1,250	2	0.656	0.125	3.052
U-403*a*	149,700	10	69	Oil-filled	800	2	0.315	0.125	2.070
U-404*a*	149,700	15	69	Oil-filled	800	2	0.315	0.125	2.070
U-405*a*	160,000	10	138	Oil-filled	900	1	0.560	0.141	2.646
U-406*a*	160,000	15	138	Oil-filled	900	1	0.560	0.141	2.646
U-41*a*	255,000	10	138	Oil-filled	750	2	0.560	0.141	2.562
U-42*a*	247,500	10	230	Oil-filled	400	2	0.925	0.156	3.234
U-43*a*	255,000	15	138	Oil-filled	750	2	0.560	0.141	2.562
U-44*a*	247,500	15	230	Oil-filled	400	2	0.925	0.156	3.234
U-441*a*	378,000	10	230	Oil-filled	1,000	2	0.925	0.156	3.556
U-442*a*	378,000	15	230	Oil-filled	1,000	2	0.925	0.156	3.556
U-45*a*	600,000	10	230	Oil-filled	600	4*	0.925	0.156	3.352
U-46*a*	600,000	15	230	Oil-filled	600	4*	0.925	0.156	3.352

The system identification number is kept throughout the entire study.

The 69-kv and 138-kv oil-filled cables have an 0.500-inch hollow core, and the 230-kv cables have an 0.690-inch core.

*Systems *U*-45*a* and *U*-46*a* have two duct banks, two circuits per duct bank.

Table II. System Major Equipment Items

System Identification Number	Sending-End Transformers—Total System Kva	Receiving-End Transformers—Total System Kva	High-Voltage Oil Circuit Breakers—Number of Breakers in System and Their Interrupting Capacity*	High-Voltage Air-Break Disconnectors—Total Number in System and Their Ampere Rating†
U-33a	67,900	63,800	6–500	12–600
U-331a	66,733	64,050	6–500	12–600
U-34a	81,200	78,400	6–750	12–600
U-35a	68,367	65,800	6–500	12–600
U-351a	67,550	64,050	6–500	12–600
U-36a	81,783	78,400	6–750	12–600
U-361a	94,033	91,233	6–1,000	12–600
U-362a	94,617	91,233	6–1,000	12–600
U-363a	96,600	93,217	6–1,000	12–600
U-364a	97,617	93,217	6–1,000	12–600
U-37a	129,150	125,533	6–1,000	12–600
U-371a	132,533	128,333	6–1,000	12–600
U-38a	127,983	124,250	6–1,500	12–600
U-39a	129,733	125,533	6–1,000	12–600
U-391a	133,350	128,333	6–1,000	12–600
U-40a	128,683	124,250	6–1,500	12–600
U-401a	200,000	194,500	14–1,500	28–600
U-402a	200,875	194,500	14–1,500	28–600
U-403a	201,125	194,500	14–1,500	28–600
U-404a	202,500	194,500	14–1,500	28–600
U-405a	211,125	205,625	10–1,500	20–600
U-406a	211,750	205,625	10–1,500	20–600
U-41a	336,500	327,750	20–2,500; 4–1,500	48–600
U-42a	321,375	314,500	24–2,500	48–1,200
U-43a	337,625	327,750	20–2,500; 4–1,500	48–600
U-44a	322,375	314,500	24–2,500	48–1,200
U-441a	392,700	384,500	20–3,500; 4–2,500	48–1,200
U-442a	393,400	384,500	20–3,500; 4–2,500	48–1,200
U-45a	624,000	611,000	24–5,000; 12–3,500	72–1,200
U-46a	625,500	611,000	24–5,000; 12–3,500	72–1,200

Sending-end and receiving-end transformer kilovolt-amperes include spare transformer capacity as follows: Systems *U-33a* to *U-40a*, inclusive, have one single-phase spare unit; systems *U-401a* to *U-44a*, inclusive, have a spare three-phase bank. Systems *U-441a* to *U-45a*, inclusive, have no spare kilovolt-ampere capacity; their transformers permitting a 25-per-cent overload for two hours (Overload accounted for in system cost).

*First figure indicates number of three-phase oil circuit breakers; second figure indicates breaker interrupting capacity in megavolt-amperes.

†First figure indicates number of three-phase air-break disconnectors; second figure indicates disconnector current rating.

Figure 5. Division of capital costs of sending and receiving substations into their major component parts, in transmission systems ten miles long

A—Land
B—Structures
C—Power transformers
D—High-voltage switching and protective equipment
E—Low-voltage switching, protective and control equipment
F—Auxiliary substation equipment

Dash-and-dot lines represent those parts of the receiving-end substation which differ substantially from the sending-end percentages (*C* and *E*)

are provided with a relay cable (pilot wire), and the oil-filled-cable lines have an oil-signal cable for each power-cable circuit. Two wires of the relay and the oil-signal cables are used for communication purposes.

The system major equipment items are given in Table II.

General Principles of System Design

Since the systems studied are parts of existing metropolitan systems, the position is taken that no other transmission systems in the vicinity depend on them for continuity of operation, but rather the reverse is the case. Therefore the underground lines are designed to have as many circuits as are necessary for the transmission of the specified block of power, no provision being made for spare circuits or spare single cables.

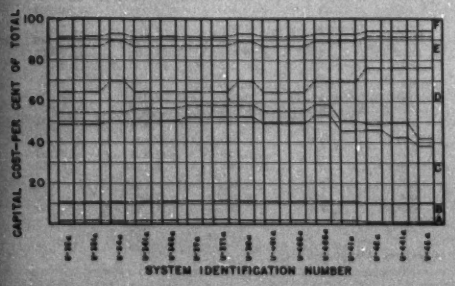
Voltages at which transmission is being effected are those which appear suitable for the particular block of power transmitted. No attempt is being made to secure the economical loading of cables for a certain cyclic load. However, the accepted annual load factor, loss factor relationship,[6,7] is used throughout the study. The selection of the cable copper cross section is made from temperature considerations, calculations being based on the cable summer rating. No credit is given for the charging current of cables.

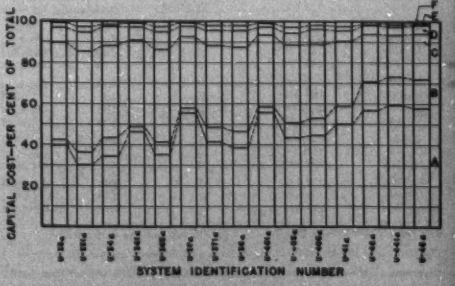
A study of underground transmission systems shows that stability is no problem in these systems, neither steady-state nor transient stability. Therefore round-rotor machines of standard design are applicable, no stability-improving devices are required, and standard breakers are used of eight-cycle opening time. For this reason, as well as for voltage regulation purposes, no synchronous condensers are placed at the receiving end of the system. Voltage drop in an underground line being very small, voltage is assumed to be controlled by adjustment of the reactive power of the receiving-end steam-station generators, supplementing the plus-minus-ten-per-cent load-ratio control of the receiving transformers.

System rating is expressed in kilovolt-amperes and is equal to the rating of all cable circuits. The rating of terminal equipment installed is obtained by adding to the system rating all the losses in all parts of the power-transmission system, at appropriate power factors.

Figure 6. Division of capital cost of the transmission line into its component parts, in transmission systems ten miles long

A—Cables
B—Cable accessories
C—Duct banks
D—Manholes
E—Bonding
F—Equipment for communication and relaying





Underground-Line Design Data

In choosing the size of the underground cable required for the transmission of a certain block of power, the maximum allowable temperature of cable insulation is taken as the determining factor. This temperature is taken at 60 degrees centigrade for the solid cables, and at 70 degrees centigrade for the oil-filled cables, with the base temperature of the earth at 20 degrees centigrade. Losses and voltage drops are taken as obtained for these current-temperature conditions.

The selection of the 69-kv solid cables is made on the basis of the Insulated Power Cable Engineers' Association tables,[8] for cables laid in ducts, for 100-per-cent daily load factor. The kilovolt-ampere rating of these cables is taken for current-carrying capacities as given in these tables. The selection of the 69-kv, 138-kv, and 230-kv oil-filled cables is made from data obtainable in literature[9, 10] and from tables supplied by the cable manufacturers. In every case tables were used for cables laid in ducts, and where the cable winter rating is given the ratio of summer to winter rating was taken at 0.85. There being no standards for the current-carrying capacity of the oil-filled cables generally accepted by the industry, in the same sense as are accepted the IPCEA tables for solid cables, the current rating of these cables is taken as obtained by calculation for each case; and the kilovolt-ampere rating of the oil-filled cables is based on the permissible current calculated.

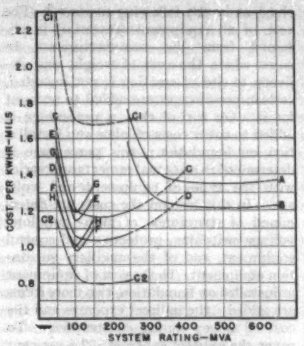


Figure 7. Cost of the entire system, including terminal substations, per kilowatt-hour

For explanation of identification letters, see Figure 1. All costs at 50 per cent annual load factor except as follows:

C1...15..138 at 35 per cent
C2...15..138 at 75 per cent annual load factor

For the calculation of permissible current-carrying capacities, the insulation thickness, thickness of lead sheath, and the dielectric power factor of cables were taken as recommended by the Association of Edison Illuminating Companies[11] and as given by the manufacturers. The calculation of the cable outside diameter, of its geometric factor, of the thermal resistance to I^2R loss and to dielectric loss between conductor and base, the calculation of current rating and of the cable three-phase dielectric loss were made as recommended by Simmons.[12, 13]

All cables have special bonding.[14] Sheath voltage per length of cable between manholes was calculated, and wherever this voltage at rated current loading exceeds 11 volts the series impedance bonding is used. Bonding transformers are installed in the manholes for the joints. The percentage residual sheath losses allowed after special bonding is 5 in 69-kv cables, ten in 138-kv and 20 in 230-kv cables.

In determining the number of normal joints and stop joints, the practice recommended by cable manufacturers and given in the literature[15] was followed. The length of a section for oil-filled cables is taken at one mile; lines are assumed to be of a substantially level profile. The distance between manholes for solid cables is 754 feet, and for oil-filled cables 660 feet. The pilot-wire and oil-signal cables are placed in separate ducts, so

Table III. Ducts, Manholes, and Cable Accessories

System Identification Number	Joints, Number in System		Ducts		Manholes, Number in System			Reservoirs—Type, Capacity, and Number in System*		
	Normal Joints	Stop Joints	Conduit Size, Inches	Number of Ducts in a Bank	For Normal Joints	For Stop-Joints	For Reservoirs	CC—Feeder or Gravity Type	AC—Gas-in-Cell Type	DC—Oil-in-Cell Type
U-33*a*	207		3.5	4	69					
U-331*a*	210	33	3.5	4	70	11	9	6-9	6-9	48-9
U-34*a*	210	33	3.5	4	70	11	9	6-15	6-14	48-15
U-35*a*	312		3.5	4	104					
U-351*a*	315	48	3.5	4	105	16	14	6-9	6-9	78-9
U-36*a*	315	48	3.5	4	105	16	14	6-15	6-14	78-15
U-361*a*	207		3.5	4	69					
U-362*a*	312		3.5	4	104					
U-363*a*	210	33	3.5	4	70	11	9	6-12	6-12	48-12
U-364*a*	315	48	3.5	4	105	16	14	6-12	6-12	78-12
U-37*a*	207		4.5	4	69					
U-371*a*	210	33	3.5	4	70	11	9	6-15	6-14	48-15
U-38*a*	210	33	3.5	4	70	11	9	6-18	6-14	48-15
U-39*a*	312		4.5	4	104					
U-391*a*	315	48	3.5	4	105	16	14	6-15	6-14	78-15
U-40*a*	315	48	3.5	4	105	16	14	6-18	6-14	78-15
U-401*a*	414		4.5	7	69					
U-402*a*	624		4.5	7	104					
U-403*a*	420	66	3.5	7	70	11	9	12-12	12-12	96-12
U-404*a*	630	96	3.5	7	105	16	14	12-12	12-12	156-12
U-405*a*	210	33	3.5	4	70	11	9	6-19	12-9	48-18
U-406*a*	315	48	3.5	4	105	16	14	6-19	12-9	78-18
U-41*a*	420	66	3.5	7	70	11	9	12-19	24-9	96-18
U-42*a*	420	66	4.5	7	70	11	9	24-18	36-12	192-15
U-43*a*	630	96	3.5	7	105	16	14	12-19	24-9	156-18
U-44*a*	630	96	4.5	7	105	16	14	24-18	36-12	312-15
U-441*a*	420	66	4.5	7	70	11	9	24-19	36-12	192-18
U-442*a*	630	96	4.5	7	105	16	14	24-19	36-12	312-18
U-45*a*	840	132	4.5	7	140	22	18	48-18	72-12	384-18
U-46*a*	1,260	192	4.5	7	210	32	28	48-18	72-12	624-18

Number of normal joints in 69-kv solid cables is seven per mile. In all the oil-filled cables seven normal joints and one stop joint per mile are used.

All manholes are of straight type, made of concrete. All manholes and duct banks paved with eight-inch concrete.

*First figure indicates number of reservoirs in system; second, the reservoir unit capacity in gallons.

that in each system a duct bank has one more duct than there are single-conductor cables. Separate manholes are provided for normal joints, for stop joints, and for the reservoirs. Three types of reservoirs are used—the *CC*, *AC*, and *DC* types.

The detailed data on ducts, manholes, and cable accessories are given in Table III.

Method of Estimating System Capital Cost

For the purpose of estimating the capital cost, the system is divided into the following three groups:

1. The sending-end substation.
2. The underground line.
3. The receiving-end substation.

The subdivisions of the groups are shown in Table IV, which gives a typical calculation of system capital cost.

The capital cost of each group is arrived at in the following manner:[5] The cost of all equipment (material) is obtained from the manufacturers. In cases where the cost of freight and delivery to site of erection is not included, certain percentages are added to account for it. On top of this, a percentage is added to cover costs of labor and installation on foundation; this percentage is determined from actual projects and varies with the type of equipment and voltage. In this fashion the costs are determined of structures, of high- and low-voltage switching, protective and control equipment, and of the auxiliary substation equipment. To the cost of equipment as installed on foundation, two more items are added: the indirect expenses and the cost of money during construction. To cover the indirect expenses, 22.5 per cent is added. The cost of money is taken at six per cent for one-half the length of the construction period, which is taken at six months for all the systems under study.

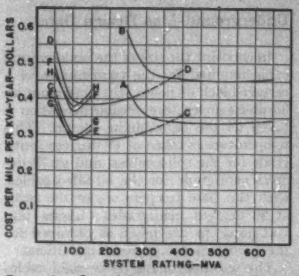


Figure 8. Cost of the entire system, including terminal substations, per mile per kilovolt-ampere-year at 50 per cent annual load factor

For explanation of identification letters, see Figure 1. Costs per mile per kilovolt-ampere-year at 35 and 75 per cent annual load factors differ very little from the cost at 50 per cent annual load factor

Table IV. Typical Calculation of Total System Capital Cost—System *U*-41a

In Dollars

	Cost of Item as Delivered (Material)	Cost of Item as Installed (on Foundation Where Needed) Including Labor Cost	Group Cost
1. Sending substation			
1.1 Land	33,700	33,700	
1.2 Structures		206,500	
1.3 Power transformers	629,000	754,800	
1.4 High-voltage switching equipment			
1.41 oil circuit breakers	271,600	325,900	
1.42 air-break disconnectors	61,200	73,450	
1.43 busses and supports		115,400	
1.5 Low-voltage switching, protective, and control equipment		500,000	
1.6 Auxiliary substation equipment		154,000	
		2,163,750	
Indirect expenses		486,850	
Cost of money during construction		39,800	2,690,400
2. Line			
2.1 Underground cables*	669,000	669,000	
2.2 Cable accessories*			
2.21 terminals	4,550	4,550	
2.22 joints	64,100	64,100	
2.23 reservoirs	48,150	48,150	
2.24 oil	900	900	
2.3 Duct banks*		421,300	
2.4 Manholes*		68,400	
2.5 Bonding		32,400	
2.6 Equipment for communication and relaying	24,700	29,600	
		1,338,400	
Indirect expenses		301,150	
Cost of money during construction		24,550	1,664,100
3. Receiving substation			
3.1 Land	33,700	33,700	
3.2 Structures		206,500	
3.3 Power transformers	727,000	872,400	
3.4 High-voltage switching equipment			
3.41 oil circuit breakers	271,600	325,900	
3.42 air-break disconnectors	61,200	73,450	
3.43 busses and supports		115,400	
3.5 Low-voltage switching, protective, and control equipment		432,500	
3.6 Auxiliary substation equipment		154,000	
		2,213,850	
Indirect expenses		498,100	
Cost of money during construction		40,650	2,752,600
Total system capital cost			7,107,100

System *U*-41a is rated at 255,000 kva. Power is transmitted over a distance of 10 miles, at a voltage of 138 kv, over two circuits of a 750,000-circular-mil oil-filled cable.

Construction period taken at six months. Cost of money during construction taken at six per cent for one-half construction period.

*Cost of duct banks includes the cost of laying cable and affixing terminals. Cost of manholes includes affixing joints and placing reservoirs.

All prices are based on a cost of copper of $10^1/_8$ cents per pound of ingot copper, and on a cost of lead of 4.6 cents per pound, fob, New York. Cost of fabricated steel of shapes involved in substation structures is taken at $102 per ton, fob, Pittsburgh.

The kilovolt-ampere rating of power transformers at both ends of the system having been increased to cover appropriate losses in system parts, the losses thus become capitalized.

Discussion of System Capital Cost

Capital cost of the systems under study is calculated per kilovolt-ampere transmitted and per kilovolt-ampere-mile for the system as a whole, including terminal substations, and for the underground line alone. The total capital cost figures are given in Table V. The capital cost of the entire system is represented in Figures 1 and 2, and that of the transmission line in Figures 3 and 4. The costs of major subdivisions of the costs of the substations and of the transmission line, in per cent of their total costs, are represented in Figures 5 and 6.

The results obtained show that there is a definite relationship between the block of power transmitted (system rating) and the transmission voltage. As the block of power transmitted increases, the cost of the entire system and of the transmission line per kilovolt-ampere and per kilovolt-ampere-mile at first decreases; then, having reached a certain minimum, it increases again. The most economical block of power, therefore, is not the largest that may be transmitted with a certain type of cable at a certain voltage.

At a rating under 65,000 kva the 69-kv solid cable is unquestionably the most economical. As the system rating increases, the 69-kv oil-filled cable comes

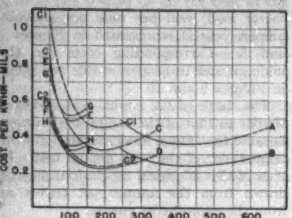


Figure 9. Cost of the transmission line per kilowatt-hour

For explanation of identification letters, see Figure 1. All costs at 50 per cent annual load factor except as follows:

C1...15..138 at 35 per cent
C2...15..138 at 75 per cent annual load factor

definitely into the picture. The over-all cost of the entire system, and of the underground line alone, for this cable is the lowest when somewhat over 100,000 kva is transmitted. With system ratings above 65,000 kva and up to almost 100,000 kva there is very little difference in the cost of the underground line alone whether a 69-kv oil-filled or a 138-kv cable is used; with still higher system ratings, a 138-kv oil-filled cable is very much more economical. When, however, the system as a whole is considered, the lower cost of the 69-kv terminal equipment extends the application of the 69-kv oil-filled cable up to ratings as high as 125,000 kva. For the 138-kv oil-filled cable the over-all cost of the entire system is the lowest when about 150,000 kva is transmitted; for the cable line alone the lowest cost is obtained with a transmission of about 200,000 kva. The different economical power limits in the two cases, when the costs of the entire system and of the transmission line alone are considered, is due to the high cost of the terminal substations compared with the cost of the underground line in systems of this voltage. The 138-kv oil-filled cable may be economically applied for transmission up to somewhat over 300,000 kva when the underground line alone is considered; and it may be used up to 375,000 kva when the entire system is evaluated, including the terminal substations. When still larger blocks of power are transmitted, then either a 230-kv oil-filled cable may be used, or the block of power should be split into a greater number of 138-kv oil-filled-cable circuits. Within the economical range of power quantities investigated, the cost of transmission with the 230-kv cable changes rather little. It is quite likely, however, that as the block of power exceeds 600,000 kva, the transmission costs will rise again, and either a different type of cable will have to be selected or an increased number of circuits will have to be used. The differences in the cost of transmission, as affected by the magnitude of the block of power, on the one hand, and the type and voltage of cable, on the other hand, are so great that a thorough study of any project is certainly warranted.

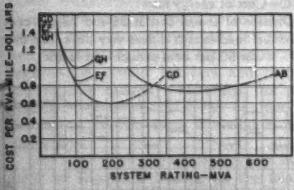


Figure 10. Cost of the transmission line per mile per kilovolt-ampere-year at 50 per cent annual load factor

For explanation of identification letters, see Figure 1. Costs per mile per kilovolt-ampere-year at 35 and 75 per cent annual load factors differ very little from the cost at 50 per cent annual load factor

The division of the system capital cost into its three component groups, given in Table V, shows that in the great majority of cases the underground line is the largest cost item in the total cost, the percentage cost depending on the relationship between the total cost of the line and the cost of the terminal equipment required for the transmission of the block of power involved. The analysis of the costs of the substations, given in Figure 5, shows that the power transformers constitute the largest cost item of both the sending and the receiving substations in all the systems except the two rated at 600,000 kva, where the circuit-breaker interrupting capacity is so high that the cost of the high-voltage switching equipment exceeds that of the power transformers. The percentage division of the capital cost of the transmission line into its main component parts, given in Figure 6, indicates that in the systems rated at 106,000 kva and more the cost of the underground cables forms the largest item of the cost of the line. Only in systems of smaller rating the cost of the duct banks represents the largest of all items; this is due to the high proportion of labor costs in the duct banks. The cost of cable accessories in the 230-kv oil-filled cable lines is very much higher than that in the 69- and 138-kv cable systems.

The percentage division of the capital cost into its component parts makes it possible to evaluate the effect of changes in the cost of system parts or in the cost of basic materials, when it is desired to consider costs different from those employed in the paper. By multiplying the percentage change in the cost of a particular item, or, for example, in the price of copper, by the corresponding percentage given for that item in the figures, the de-

Table V. Capital and Annual System Cost

In Thousands of Dollars

System Identification Number	Capital Cost				Total Annual System Cost at 50-Per-Cent Annual Load Factor
	Entire System	Sending Substation	Receiving Substation	Transmission Line	
U-33a	1,759	496	511	752	251
U-331a	1,725	499	504	732	255
U-34a	2,321	717	735	769	320
U-35a	2,138	498	513	1,127	301
U-351a	2,093	493	505	1,095	309
U-36a	2,613	721	736	1,156	364
U-361a	2,140	634	658	848	311
U-362a	2,567	638	659	1,270	367
U-363a	2,113	646	670	797	315
U-364a	2,516	950	873	1,193	373
U-37a	2,079	810	835	1,034	390
U-371a	2,584	827	852	905	388
U-38a	2,744	915	952	877	402
U-39a	3,195	812	836	1,547	457
U-391a	3,037	828	853	1,356	453
U-40a	3,185	919	954	1,312	463
U-401a	4,472	1,399	1,451	1,622	640
U-402a	5,307	1,404	1,453	2,450	748
U-403a	4,232	1,399	1,451	1,383	626
U-404a	4,928	1,406	1,454	2,068	708
U-405a	4,330	1,632	1,700	998	628
U-406a	4,827	1,634	1,701	1,492	697
U-41a	7,107	2,090	2,753	1,664	1,020
U-42a	10,805	4,164	4,197	2,444	1,457
U-43a	7,938	2,694	2,754	2,490	1,139
U-44a	12,052	4,189	4,207	3,653	1,613
U-441a	12,663	4,854	5,000	2,809	1,750
U-442a	14,096	4,878	5,018	4,205	1,928
U-45a	19,810	7,272	7,412	5,126	2,722
U-46a	22,379	7,287	7,418	7,674	3,046

The total annual system cost at 35- and 75-per-cent annual load factors closely approximates the cost at the 50-per-cent factor.

Table VI. Annual Fixed Charges and Annual Expenses for Maintenance and Operation on System Parts

In Per Cent of Their Capital Cost

Item	Annual Fixed Charges					Annual Expenses for Maintenance and Operation
	Taxes	Insurance	Depreciation and Obsolescence	Interest on Money Invested	Total	
Sending substation	2.0	0.5	1.823	6.0	10.323	2.0
Transmission line	2.0		1.823	6.0	9.823	1.3
Receiving substation	2.0	0.5	1.823	6.0	10.323	2.0

Charges for depreciation and obsolescence calculated by the sinking-fund method, at six per cent per annum money cost, for a 25-year life span of all system parts.

sired changes may be evaluated[3] and applied, on a percentage basis, to the calculated costs per kilovolt-ampere or kilovolt-ampere-mile. Changes in the system design, in the accepted permissible current rating for particular cables, or in the amount of equipment used, changes in the percentage allotted to cover the indirect expenses, or in the cost of money during construction, may be similarly introduced.

Method of Estimating System Annual Cost

The system annual cost is taken as the sum of the annual fixed charges and the annual operating expenses and is calculated for annual load factors of 35, 50, and 75 per cent. Both the annual fixed charges and the annual expenses for maintenance and operation are calculated as percentages of the capital cost separately for each of the three major groups into which the capital cost structure is divided. These are given in Table VI. The cost-of-energy loss, forming a separate part of the annual operating expenses, is taken equal to the sum of the cost of generation and the cost of transmission.

Figure 11. Division of annual cost of the entire system, including terminal substations, at 50 per cent annual load factor, in transmission systems ten miles long

A—Fixed charges
B—Expenses for maintenance and operation
C—Cost of energy loss
Division of annual cost at 35 and 75 per cent annual load factors differs very little from that at 50 per cent annual load factor

The capital cost of the steam-power station is taken at $100 per kilowatt for all systems designed. The annual fixed charges of the power plant are taken at the same rate as for the substations of the system, that is 10.323 per cent. The cost of maintenance and operation of the power plant consists of three parts: fixed operating costs, taken at $1.25 per kilowatt per year; variable maintenance costs, which at the annual load factors of 35, 50, and 75 per cent are taken correspondingly at $0.875, $1.25, and $1.85 per kilowatt; and operating supplies (labor) taken at 0.25 mills per kilowatt-hour. The cost of fuel at the annual load factors of 35, 50, and 75 per cent is taken correspondingly at 1.897, 1.795, and 1.70 mills per kilowatt-hour.

The losses in various system parts are given in Table VII. For simplification purposes, losses in the underground-cable line have been taken as fully dependent on load, although, strictly speaking, this is not entirely correct, especially in the 230-kv cables. It will be observed from the table that losses in the cable line represent the largest single item of the system losses. A careful design of the cable line is therefore exceedingly important.

The cost of energy loss per kilowatt-hour for the entire system is given in Table VIII. It is calculated for an 85-per-cent power-factor load.

Discussion of System Annual Cost

The total annual system cost at 50-per-cent annual load factor is given in Table V. The cost of the entire system per kilowatt-hour (at 85-per-cent power-factor load) and per mile per kilovolt-ampere-year is represented in Figures 7 and 8. Corresponding costs for the underground transmission line are given in Figures 9 and 10.

The shape of the annual-cost curves is similar to that of the capital-cost curves, because the annual fixed charges form the largest part of the total annual cost. In view of this, identical conclusions may be drawn from the annual-cost curves as from the capital-cost curves.

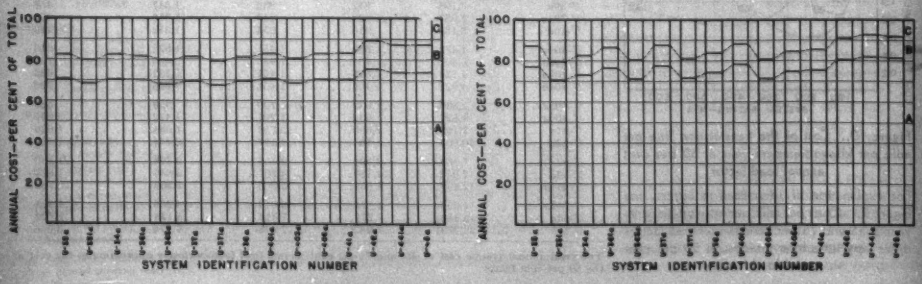
The division of the annual cost into its three major component parts at the 50-per-cent annual load factor is given in Figure 11 for the entire system and in Figure 12 for the underground line alone. The fixed charges form by far the largest percentage of the total annual cost. Any changes which may take place in the capital cost may be introduced into the annual cost through the percentages which the fixed charges form of the total annual cost. Similarly, the effect of changes which it may be desired to make in the rate of taxes, in the insurance, in the rate of depreciation and obsolescence, or in the interest on money invested may be estimated easily.[3] When the maintenance and operation costs, the cost of the energy loss, or the cost of generation are other than those taken in the study, their effect on the annual cost of the entire system, or on the cost of the underground line alone, may be evaluated in like fashion.

Effect of Design Conditions and Economic Factors on System Cost

Within the scope of this paper it is impossible to estimate the effect which the modification of the various design conditions adopted and of the economic factors assumed in the study would have on the

Figure 12. Division of annual cost of the transmission line at 50 per cent annual load factor, in transmission lines ten miles long

A—Fixed charges
B—Expenses for maintenance and operation
C—Cost of energy loss
Division of annual cost at 35 and 75 per cent annual load factors differs very little from that at 50 per cent annual load factor



cost of the system or on the cost of the transmission line.

Among the design conditions affecting the cost is the condition of service reliability. This could have been modified either by installing an extra single-conductor cable, or by requiring that systems carry full load with a loss of one circuit. The length of the oil-filled cable section and the number of joints and manholes assumed per mile could be changed in terminal equipment, of the underground cable, of labor, and installation on foundation; financial methods of cost estimates; annual fixed charges; and the cost of maintenance and operation, may also vary from those taken in the study and may affect the system cost.

In estimating the magnitude of error in the final cost figures of this study, it may be said that the error in the design is very likely less than ten per cent. Of the same order is the error in the cost figures obtained from various manufacturers. The error in estimating costs of labor and installation, and other miscellaneous costs is around 15 per cent.

Table VII. System Losses in Kilowatts

System Identification Number	Losses Independent of Load: Sending-End Transformers	Losses Independent of Load: Receiving-End Transformers	Losses Independent of Load: Total Losses	Losses Dependent on Load: Line	Losses Dependent on Load: Sending-End Transformers	Losses Dependent on Load: Receiving-End Transformers	Losses Dependent on Load: Total Losses*
U-33a	194	177	371	723	291	264	1,378
U-331a	196	176	372	1,206	281	263	1,850
U-34a	230	215	445	1,040	344	322	1,836
U-35a	195	177	372	1,081	293	264	1,738
U-351a	193	176	369	1,810	289	263	2,462
U-36a	231	215	446	1,560	347	322	2,359
U-361a	269	251	520	871	402	376	1,799
U-362a	270	251	521	1,306	405	376	2,237
U-363a	275	253	530	1,292	413	384	2,239
U-364a	278	255	533	1,938	417	384	2,889
U-37a	358	345	703	955	536	517	2,208
U-371a	367	353	720	1,433	549	529	2,711
U-38a	361	341	702	1,115	541	512	2,368
U-39a	359	345	704	1,433	537	517	2,687
U-391a	368	353	721	2,150	552	529	3,431
U-40a	363	341	704	1,673	546	512	2,931
U-401a	533	498	1,031	1,384	799	747	3,230
U-402a	535	498	1,033	2,076	803	747	3,926
U-403a	536	498	1,034	2,176	804	747	4,027
U-404a	539	498	1,037	3,265	809	747	4,121
U-405a	546	527	1,073	1,215	818	791	3,144
U-406a	548	527	1,075	1,822	822	791	3,755
U-41a	845	840	1,685	1,884	1,373	1,260	5,017
U-42a	732	705	1,437	1,464	1,100	1,059	4,123
U-43a	888	840	1,728	2,827	1,336	1,260	5,923
U-44a	734	705	1,439	2,211	1,103	1,059	4,873
U-441a	1,270	1,076	2,346	1,476	1,900	1,614	5,740
U-442a	1,274	1,076	2,350	2,214	1,906	1,614	6,484
U-45a	1,780	1,710	3,490	2,954	2,665	2,565	9,384
U-46a	1,785	1,710	3,495	4,431	2,675	2,565	10,871

Line losses are the sum of copper losses and dielectric losses in cables.

*These include losses in the current-limiting reactors.

either direction. The power factor of the load could be taken other than the assumed 85-per-cent lagging power factor, with its consequent effect on kilowatt-hour cost. Self- instead of water-cooled power transformers could be used, and their spare capacity could be modified. Finally, the system of high-voltage busses and their sectionalization, the number of high-voltage circuit breakers and their interrupting capacity, calculated for a certain assumed load, could be made somewhat different from those taken in the study.

The method of cost estimating has by itself an important bearing on the final cost. For example, had the winter rating been used for the cables instead of the summer rating, or had credit been allowed for the charging current of the underground cables, the total costs could have been appreciably lowered. The various economic factors, such as the price of copper and lead; cost of the

Summary and Conclusions

Results of design and cost estimates of cable-transmission systems and tie lines may be summarized as follows:

1. The type and voltage of the underground cable selected for a certain transmission line or tie line depend on the magnitude of the block of power to be transmitted. It is shown in the paper that, as the block of power increases beyond certain values, it becomes more economical to use a cable of higher voltage—or of a different type—rather than to employ a cable of the type and voltage which are more suitable for a smaller block of power. In particular this is evident when the 69-kv solid and oil-filled cables are being compared with the 138-kv oil-filled cable.

2. The most economical block of power is neither the smallest nor the largest that may be transmitted at a particular voltage. When properly selected, however, it will lower considerably the cost per kilovolt-ampere-mile, as well as the annual cost.

3. At prices for the 230-kv oil-filled cable and its accessories as taken in this study, this cable can compete with the 138-kv oil-filled cable only as a tie line between two 230-kv systems with available 230-kv terminal equipment. If an underground cable line requires installation of new terminal equipment, it will be very much less expensive to employ a 138-kv oil-filled cable. Otherwise a 230-kv cable tie line alone, without terminal equipment, is not much more expensive than a 138-kv cable line when a block of power of optimum value is transmitted, and at some system ratings it is the more economical.

4. The cost of the 230-kv oil-filled cable accessories as taken in this study appears to represent a very high percentage of the cost of the cable tie line. It is the cost of these accessories that limits the application of the 230-kv cable, and the lowering of it will extend considerably the region of the economical application of this cable. On the other hand, it might perhaps be possible to use sections of greater length and to place the normal joints farther apart than would follow from present-day practice.

5. Since cables in this country, as a general rule, use greater insulation for a certain voltage and operate at higher temperatures than is the practice in some European countries, the thought is expressed that it perhaps would lead to useful economic results, should a broad study be made of the relationships of the cable insulation for a certain voltage, the maximum operating temperature, the cable current-carrying capacity, and the cost of the cable. The relationship between the insulation and the current rating at the operating temperature must not be more favorable than that which would result in a satisfactory cable of a minimum cost. Such a study probably would involve an analysis of the various parts of the cable structure, such as the diameter of the hollow core and the thickness of the lead sheath. Even if such studies are being made by some companies, indications are that more extensive studies carried on by the industry as a whole, as a co-operative effort between the producers and the consumers, would bring gratifying results both to the cable manufacturers and the public utilities.

6. Figures are given showing the division on a percentage basis of the system capital and annual costs into their major component parts. Tables show the

Table VIII. Cost of Energy Loss Per Kilowatt-Hour

In Mills

System Identification Number	Annual Load Factor 35 Per Cent	50 Per Cent	75 Per Cent
U-33s	7.67	6.00	4.98
U-331s	7.67	6.01	4.98
U-34s	7.76	6.07	4.73
U-35s	7.97	6.20	4.82
U-351s	7.98	6.23	4.82
U-36s	7.95	6.20	4.82
U-361s	7.48	5.88	4.60
U-362s	7.73	6.05	4.72
U-363s	7.45	5.85	4.59
U-364s	7.67	6.01	4.98
U-37s	7.38	5.80	4.55
U-371s	7.32	5.76	4.52
U-38s	7.42	5.82	4.57
U-39c	7.59	5.94	4.65
U-391s	7.49	5.88	4.61
U-40s	7.60	5.95	4.64
U-401s	7.57	5.93	4.64
U-402s	7.80	6.09	4.75
U-403s	7.49	5.88	4.60
U-404s	7.69	6.02	4.69
U-405s	7.45	5.84	4.59
U-406s	7.58	5.94	4.64
U-41s	7.48	5.88	4.60
U-42s	8.23	6.39	4.94
U-43s	7.63	5.98	4.67
U-44s	8.45	6.53	5.04
U-441s	7.75	6.06	4.72
U-442s	7.92	6.17	4.80
U-45s	7.72	6.04	4.71
U-46s	7.90	6.17	4.80

Cost of steam generation is taken at 6.20 mills per kilowatt-hour at 35-per-cent annual load factor, 4.97 mills at 50-per-cent annual load factor, and 3.99 mills at 75-per-cent annual load factor.

Cost of transmission is calculated from the sum of the annual fixed charges and annual expenses for maintenance and operation, both taken for the entire system, terminal substations including.

amount of various equipment used in the system. Through their use, changes in the system cost may be evaluated when costs other than those used in this study are taken for the cable and its accessories, for the system equipment, for labor and installation, or for the duct banks; when prices of basic materials change; or when some of the financial factors affecting the capital or annual cost structure are modified. Similarly, the data may be used for estimating the cost when the design of some system parts, or the amount of terminal equipment, is modified; when it is desired to modify the current-carrying capacity of the cable line; when the duct banks or the number of cable accessories is changed, while at the same time the costs and economic assumptions made in the study are retained. The tables and figures may be used either for complete systems, including terminal equipment, or for the underground cable line alone, whether it be a straight transmission line, a tie line, or a cable termination of an overhead transmission line approaching the power station. The cost curves given may be interpolated within the range of values investigated.

7. This paper is an indication of the general trend of costs of underground power-transmission and tie lines. For an exact determination of the capital or annual costs of a projected system, or of an underground cable line, the costs must be calculated in detail. In some cases, with certain combinations of the various factors involved, costs lower or higher than those given in this study may be obtained. The relative costs and the effect of various factors, however, will remain as presented.

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The Direct- and Quadrature-Axis Equivalent Circuits of the Synchronous Machine

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THE EQUIVALENT-CIRCUIT method of analysis is a tool of unquestioned competence in the solution of machine and system problems involving a number of simultaneous equations. Its efficacy in obtaining practical results has been demonstrated in many diverse applications. In particular, the complete equivalent circuit of the synchronous machine—complete in the sense that the field-winding circuit and the multiple damper-winding circuits are individually included—is used whenever a detailed knowledge is needed of the operation of all the rotor circuits. Specific examples of its use are in the design of the damper-winding circuits, in problems involving single-phase and asynchronous operation, in the determination of damping and synchronizing torque, and in the determination of the transient and subtransient impedances; these few by no means exhaust the list.

When we consider the many practical applications of the complete equivalent circuit of the synchronous machine, it is somewhat surprising to note that it has been analyzed only somewhat superficially in the technical literature and has been the subject of very few technical papers, the most important of these being the papers of Linville[1] and Liwschitz.[2] Linville presented an equivalent circuit which was complete within the limits of certain well-defined approximations and also derived formulas for all the machine impedances. Liwschitz recognized that there were many applications in which the complexity of Linville's equivalent circuit would not be warranted and accordingly presented simplified equivalent circuits which were easier to use. The simplified circuits of Liwschitz give satisfactory results in many important problems, but in those applications which require a knowledge of the details of damper-winding operation the complete equivalent circuits are indispensable.

Because these complete equivalent circuits of the synchronous machine are becoming of ever-increasing importance, especially in these times with systems and machines being subjected to higher and higher specific loadings, it is the purpose of this paper to derive more complete and more exact equivalent circuits than heretofore have been available. These circuits are developed primarily for use on a-c network analyzers, since the modern analysis of problems of the type discussed in this paper tends more and more toward the use of such mechanical aids.

This paper also presents formulas for all the impedances needed by the equivalent circuits. An assemblage of the impedance formulas such as is here given is necessary when presenting an equivalent circuit in order to be certain that all the impedances are in accord and calculated on the same base. It will be found that the per-unit impedance formulas presented in this paper differ from those of Linville in that, in addition to improved permeance coefficients, the rotor current base is the x_{ad} base[3] which is more familiar to designers than the magnetomotive-force base of Linville. These impedance formulas are presented in this paper in a direct systematized form which considerably simplifies the determination of the per-unit values, and which is not subject to the misinterpretation which sometimes causes errors in the determination of the per-unit impedances of the multiple rotor circuits.

The permeance coefficients which are an integral part of the reactance formulas are determined in this paper by means of a gap-reluctance expression whose accuracy is proved by comparison with similar coefficients evaluated from flux plots. These permeance coefficients are evaluated numerically for a typical pole configuration and presented in tabular form. The specific results and a discussion of their superiority over presently available data are given in the following section.

Results and Discussion

The complete direct-axis equivalent circuit of the synchronous machine is given by Figure 1. The quadrature-axis equivalent circuit is obtained from Figure 1 merely by substituting q for d. This circuit is an improvement over previous equivalent circuits in the following particulars:

(*a*). The impedances are given in their most general form and are all present, although some can be eliminated by a suitable choice of base-current ratio in the calculation of the per-unit impedances. For instance, this paper uses a base-current ratio which makes $X_{gmmf} = X_{fad}$, and, accordingly, if the end-ring impedances can be neglected, the coupling transformers of Figure 1 are unnecessary.

(*b*). The end-ring impedance is correctly represented, and is separated from the field-winding circuit by means of 1/1 coupling transformers.

(*c*). The component impedances are given directly in terms of resistance and capacitive reactance, so that the circuit can be set up on an a-c network analyzer without introducing the resistance errors of inductive reactance. The circuit impedance $\hat{z}_d(j\omega)$ is obtained by direct measurement of the terminal voltage and current.

The equivalent circuit of Figure 1 is developed directly from the operational equations of the synchronous machine by noting the physical relations which exist between the various impedances. This development is given in the section, "Development of Equivalent Circuits."

The per-unit impedances for use in the equivalent circuit of Figure 1 are developed in the sections, "Impedances of Direct-Axis Circuits" and "Impedances of Quadrature-Axis Circuits." Because of the large number of formulas so obtained, it is not practical to collect and present them in this section. The origin of most of the difficulties in the determination of these multitudinous impedances is in the stator–rotor turn ratio of the short-pitched damper-winding circuits. In order to maintain a consistent stator–rotor turn ratio and thereby obtain an harmonious system of per-unit impedances, the latter are evaluated herein by first determining the physical ampere-inch-second impedances, and converting these to per unit by the direct conversion factors previously published by the author.[3] In the author's judgment, this method is superior to any other method presently available, since the physical concept of the impedance is maintained up to the last step at which point the per-unit impedances are obtained merely by introducing the conversion factor. In addition, the stator–

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rotor turn ratio is used systematically without possibility of error.

The rotor-current base selected for the per-unit impedances of this paper is the so-called x_{ad} base which is the base which makes X_{afd} numerically equal to x_{ad}. This base has been selected, because it is the base in most common use among designers, and most design formulas are based on it. If desired, however, the per-unit impedances can be converted to any other base by the consistent expressions previously published.[3]

The permeance coefficients necessary for the reactance formulas of the multiple damper-winding circuits are evaluated in Appendixes I and II by numerical integration of definite integrals based on a reluctance expression developed from a study of the work of Doherty and Nickle.[4] These coefficients are evaluated for a typical pole configuration, and the resulting numerical values are given in Table I. Design experience has indicated that these permeance coefficients are more accurate than any previously published, especially in the quadrature axis. A direct indication of their accuracy is given by comparison with the work of Wieseman[5] who evaluated similar quantities for the field-winding circuit from actual flux plots. The correspondence with the work of Wieseman is given in Table II.

The definite-integral expressions for the pole-shape coefficients as derived in this paper are not intended to compete with any future evaluation by flux plotting but instead are offered as an acceptable and satisfactory solution until more accurate values can be obtained from flux plots and design experience. The author believes, however, and the correspondence with the work of Wieseman substantiates this belief, that these integrals are sufficiently accurate that future investigations can be directed at complementary correction factors for strategic points rather than at complete new integrals or tabular values.

Numbering of Damper-Bar Circuits

Particular attention is called to the numbering of the damper-bar circuits. This numbering system is shown on Figure 2. The numbering of the physical bars proceeds outward from the polar axis. If a single bar lies directly on the polar axis, it should be hypothetically divided at its center line with the two halves thus becoming bar 1 on each side of the polar axis.

The numbering of the direct-axis circuits is identical with the numbering of the physical bars, and proceeds outward from the direct or polar axis. In contradistinction to the direct-axis circuits, the numbering of the quadrature-axis circuits proceeds outward from the quadrature or interpolar axis. The advantage of this method is that all the logic and equivalent circuits developed for one axis are immediately applicable to the other axis with only a change of subscript from d to q or vice versa. The disadvantage is that the term n, upon superficial examination, seems somewhat ambiguous since the same bar has one number in the direct axis and another in the quadrature axis. This superficial ambiguity is eliminated by noting that the subscript n followed by d specifies the nth circuit numbered from the direct axis, the subscript n followed by q specifies the nth circuit numbered from the quadrature axis, and the subscript n without either d or q following specifies the nth physical bar numbered from the polar axis.

Analysis

Development of Equivalent Circuits

The generalized per-unit equations 1a, b, ... and 2a, b, ... were derived in a recent publication by the author.[3]

$$\psi_d = X_{afd}I_{fd} + X_{a1d}I_{1d} + X_{a2d}I_{2d} + \ldots - x_d i_d \quad (1a)$$

$$\Psi_{fd} = X_{ffd}I_{fd} + X_{f1d}I_{1d} + X_{f2d}I_{2d} + \ldots - X_{fad}i_d \quad (1b)$$

$$\Psi_{1d} = X_{1fd}I_{fd} + X_{11d}I_{1d} + X_{12d}I_{2d} + \ldots - X_{1ad}i_d \quad (1c)$$

$$\Psi_{2d} = X_{2fd}I_{fd} + X_{21d}I_{1d} + X_{22d}I_{2d} + \ldots - X_{2ad}i_d \quad (1d)$$

$$E_{fd} = p\Psi_{fd} + R_{ffd}I_{fd} + R_{f1d}I_{1d} + R_{f2d}I_{2d} + \ldots \quad (2a)$$

$$E_{1d} = p\Psi_{1d} + R_{1fd}I_{fd} + R_{11d}I_{1d} + R_{12d}I_{2d} + \ldots \quad (2b)$$

$$E_{2d} = p\Psi_{2d} + R_{2fd}I_{fd} + R_{21d}I_{1d} + R_{22d}I_{2d} + \ldots \quad (2c)$$

The corresponding equations in the quadrature axis can be written from equations 1a, b, ... and 2a, b, ... by substituting q for d.

If all the rotor-circuit voltages are zero, the foregoing equations reduced to equations 3a, b, ...

$$\psi_d = X_{afd}I_{fd} + X_{a1d}I_{1d} + X_{a2d}I_{2d} + \ldots - x_d i_d \quad (3a)$$

$$0 = \left(X_{ffd} + \frac{R_{ffd}}{p}\right)I_{fd} + \left(X_{f1d} + \frac{R_{f1d}}{p}\right)I_{1d} + \left(X_{f2d} + \frac{R_{f2d}}{p}\right)I_{2d} + \ldots - X_{fad}i_d \quad (3b)$$

$$0 = \left(X_{1fd} + \frac{R_{1fd}}{p}\right)I_{fd} + \left(X_{11d} + \frac{R_{11d}}{p}\right)I_{1d} + \left(X_{12d} + \frac{R_{12d}}{p}\right)I_{2d} + \ldots - X_{1ad}i_d \quad (3c)$$

$$0 = \left(X_{2fd} + \frac{R_{2fd}}{p}\right)I_{fd} + \left(X_{21d} + \frac{R_{21d}}{p}\right)I_{1d} + \left(X_{22d} + \frac{R_{22d}}{p}\right)I_{2d} + \ldots - X_{2ad}i_d \quad (3d)$$

It is evident from equations 3a, b, ... that Ψ_d and all the rotor currents are

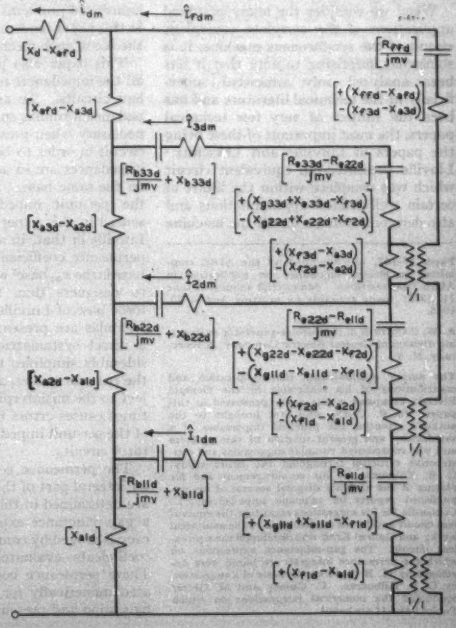


Figure 1. Direct-axis complete equivalent circuit for five or six bars per pole, $\hat{x}_d(jmv)$

$\frac{R}{jmv}$ = capacitive reactance

x = resistance

The quadrature-axis complete equivalent circuit is obtained from this circuit by substituting q for d.

Table I. Pole-Shape Coefficients Evaluated for a Typical Pole Configuration

$\rho=1.50 \quad \alpha=0.70 \quad p_p{}^{-1}g=0.03$

y_{nd}, y_{nq}	$D_{d\alpha n}y_{nd}$	$D_{q\alpha n}y_{nq}$	D_{d1n}	D_{q1n}
0	0	0	0	0
0.1	0.157	0.0316	0.198	0.0394
0.2	0.310	0.0690	0.388	0.0858
0.3	0.457	0.123	0.562	0.148
0.4	0.598	0.210	0.713	0.243
0.5	0.726	0.329	0.839	0.348
0.6	0.845	0.460	0.938	0.466
0.7	0.933	0.598	0.996	0.558
0.8	0.986	0.747	1.022	0.630
0.9	1.024	0.900	1.034	0.676
1.0	1.056	1.056	1.037	0.692

linear operational functions of i_q. If i_d is assumed to have the vectorial form, equation 4, then ψ_d and the rotor currents must have the vector forms, equations 5a, b, c. The mv notation of equations 4 and 5a, b, c is used, because it is adaptable to different machine operating conditions. The m specifies the order of the harmonic when any are present, and the v is a generalized rotor-velocity term. For asynchronous operation at constant slip s and with only fundamental currents flowing, v is replaced by s, and m equals unity only and may be dropped. For asynchronous single-phase operation, harmonics are present, and m is needed to define the particular harmonic being studied, and v becomes equal to the rotor velocity.

$$i_d=\mathcal{E}_{dm}\epsilon^{+jmvt} \tag{4}$$

$$\psi_d=\hat{\psi}_{dm}\epsilon^{+jmvt}; \quad I_{fd}=I_{fdm}\epsilon^{+jmvt}; \quad I_{nd}=I_{ndm}\epsilon^{+jmvt} \tag{5a, b, c}$$

Substituting equations 4 and 5a, b, c into equations 3a, b, ..., using only the steady-state solution of the operational equations, and canceling the exponentials gives equations 6a, b, ...

$$\hat{\psi}_{dm}=X_{afd}I_{fdm}+X_{a1d}I_{1dm}+X_{and}I_{ndm}+\ldots-x_dI_{dm} \tag{6a}$$

$$0=\left(X_{ffd}+\frac{R_{ffd}}{jmv}\right)I_{fdm}+\left(X_{f1d}+\frac{R_{f1d}}{jmv}\right)I_{1dm}+\left(X_{fnd}+\frac{R_{fnd}}{jmv}\right)I_{ndm}+\ldots-X_{fad}I_{dm} \tag{6b}$$

$$0=\left(X_{1fd}+\frac{R_{1fd}}{jmv}\right)I_{fdm}+\left(X_{11d}+\frac{R_{11d}}{jmv}\right)I_{1dm}+\left(X_{1nd}+\frac{R_{1nd}}{jmv}\right)I_{ndm}+\ldots-X_{1ad}I_{dm} \tag{6c}$$

$$0=\left(X_{nfd}+\frac{R_{nfd}}{jmv}\right)I_{fdm}+\left(X_{n1d}+\frac{R_{n1d}}{jmv}\right)I_{1dm}+\left(X_{nnd}+\frac{R_{nnd}}{jmv}\right)I_{ndm}+\ldots-X_{nad}I_{dm} \tag{6d}$$

Equations 6a, b, ... can be applied to the subject problem by recognizing the physical relations which exist between the self- and mutual impedances of the various rotor circuits. These relations are introduced in the following paragraphs. They are the foundation for the direct- and quadrature-axis equivalent circuits.

Consider the nth additional rotor circuit in the direct axis. The reactance X_{and} is the sum of the reactance due to the air-gap flux within the bars which form the nth additional rotor circuit, the reactance due to the leakage flux in the bar slots, and the reactance due to the end-ring flux.

$$X_{and}=X_{gand}+X_{band}+X_{eand} \tag{7a}$$

The mutual reactance X_{akd} between the nth additional rotor circuit and any outer additional rotor circuit k is the sum of the reactance due to the air-gap flux and the reactance due to the end-ring flux; the bar-slot flux is pure leakage.

$$X_{akd}=X_{eand}+X_{eand} \quad (k>n) \tag{7b}$$

The mutual reactance between the nth additional rotor circuit and any inner additional rotor circuit is obtainable from the inner-circuit reactances. This important relation is a direct result of the reciprocal per-unit mutual impedances to which attention was directed in previous publications.[3,6]

The mutual reactance between the nth additional rotor circuit and the field-winding circuit depends upon only the air-gap flux of the nth additional rotor circuit, since the bar-slot flux and the end-ring flux are not mutual with the field winding. These mutual reactances are reciprocal because of the reasons stated in the preceding paragraph.

Concerning the resistance components, the resistance of the nth additional rotor circuit is the sum of the bar and end-ring resistances of that circuit.

$$R_{and}=R_{band}+R_{eand} \tag{7c}$$

The mutual resistance between the nth additional rotor circuit and any outer additional rotor circuit k is the end-ring resistance of the nth circuit, since the bar resistance is not mutual with the kth circuit.

$$R_{akd}=R_{eand} \quad (k>n) \tag{7d}$$

The mutual resistance between the nth circuit and any inner circuit is obtained from the inner-circuit resistances as these mutual impedances are reciprocal.

There are no mutual resistances between the additional rotor circuits and the field-winding circuits since these circuits are coupled only magnetically.

The impedances of the quadrature-axis circuits can be written directly from the preceding expressions by substituting q for d.

When the physical relations of the preceding paragraphs are introduced into equations 6a, b, ... the equations obtained can be electrically duplicated by the a-c circuit of Figure 1 with $\hat{\psi}_{dm}$ the alternating voltage across the terminals. Figure 1 is therefore the equivalent circuit of the direct-axis equations of a synchronous machine.

In regard to equations 3a, b, ..., the relation between ψ_d and i_d may be written operationally as in equation 8a.

$$\psi_d=-x_d(p)i_d \tag{8a}$$

Substituting equations 4 and 5a, b, c and taking only the steady-state solution reduces equation 8a to equation 8b.

$$\hat{x}_d(jmv)=-\frac{\hat{\psi}_{dm}}{\mathcal{E}_{dm}} \tag{8b}$$

Reversing the direction of $\mathcal{E}_{dm}$ in Figure 1 permits $\hat{x}_d(jmv)$ to be defined as the a-c impedance of the direct-axis equivalent circuit since $\hat{\psi}_{dm}$ is the voltage across the circuit and $-\mathcal{E}_{dm}$ is the current into it. $\hat{x}_q(jmv)$ can be obtained in an analogous manner from the quadrature-axis equivalent circuit.

The current moduli $\mathcal{O}_{ndm}$ are defined as the rotor-circuit currents obtained when the terminal current $\mathcal{E}_{dm}$ is equal to $1.00\underline{/0}$. $\mathcal{O}_{nqm}$ is analogously defined.

$$\mathcal{O}_{ndm}=I_{ndm} \text{ for } \mathcal{E}_{dm}=1.00\underline{/0} \tag{9a}$$

The rotor-circuit currents I_{ndm} and I_{nqm} are obtained from the product of the actual terminal current $\mathcal{E}_{dm}$ and the corresponding modulus as shown in equation 9b, c. The terminal currents $\mathcal{E}_{dm}$ and $\mathcal{E}_{qm}$ are determined by the machine operating conditions.

$$I_{ndm}=\mathcal{O}_{ndm}\mathcal{E}_{dm}; \quad I_{nqm}=\mathcal{O}_{nqm}\mathcal{E}_{qm} \tag{9b, c}$$

The actual currents in the physical damper bars (as distinguished from the sub-d and sub-q currents in the hypothetical direct- and quadrature-axis circuits which are introduced only to simplify the mathematics) are given by equations 9d, e. It is evident from these expressions that, in general, there is unequal loading of the bars in the leading and trailing pole halves. The degree of this inequality depends upon the pole saliency and lack of symmetry between the direct- and quadrature-axis circuits. Equal loading of the trailing and leading pole halves exists only when I_{nd} and I_{nq} are in time quadrature.

Bars on trailing pole halves:

$$I_{nm}=+I_{ndm}+I_{nqm} \tag{9d}$$

Bars on leading pole halves:

$$I_{nm}=-I_{ndm}+I_{nqm} \tag{9e}$$

Due consideration must be given to the numbering system previously described by which the direct-axis circuits are numbered from the direct axis, and the quadrature-axis circuits are numbered from the quadrature axis. For instance, the third bar from the direct axis in Figure 2 is the second bar from the quadrature axis, and the total current in this bar (in the trailing half) is as given by equation 9f.

$$I_{sm}=I_{sdm}+I_{sqm} \tag{9f}$$

Impedances of Direct-Axis Circuits

Experience in the use of these equivalent circuits has shown that the safest and shortest method of calculating the per-unit impedances is first to determine the ampere-inch-second values and convert these to per-unit values by the conversion factors previously published.* This method is followed in this paper.

Unit field current as used hereinafter is that field current which will induce in each stator phase a voltage of $x_{ad}i_{ao}$. Let this current be I_{fdo}. The corresponding base-current ratio is given by equation 10a. This base current has the advantage that it makes X_{afd} numerically equal to x_{ad} and at once eliminates the necessity for differentiating between these two quantities. In a previous paper[7] the author has suggested the universal adoption of this current as a preferred base.

$$\frac{I_{fdo}}{(3/2l)_{ao}}=\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}\frac{N}{K_pK_dP_1}\frac{1}{N_{fd}} \tag{10a}$$

The unit current for the additional rotor circuits as used hereinafter will be that current which when flowing in the additional rotor circuit of 100-per-cent pitch will induce in each stator phase a voltage $x_{ad}i_{ao}$. Let this current be I_{xdo}. The corresponding base-current ratio is given by equation 10b. A 100-per-cent-pitch circuit is not usually present in modern synchronous machines, but it is convenient to use it as a base circuit since it has maximum effectiveness.

$$\frac{I_{xdo}}{(3/2l)_{ao}}=\frac{4}{\pi}\frac{A_{d1}}{D_{d1\pi}}\frac{N}{K_pK_dP_1} \tag{10b}$$

Base stator inductance L_{ao} and fundamental flux per pole at rated voltage will be needed for the evaluation of the per-unit impedances. These quantities are expressed in the following in terms of machine dimensions.

$$\beta'_{max}=3.19\frac{F_g}{g}\qquad \beta'_{tand}=3.19\frac{F_g}{g}F_{d1} \tag{11a, b}$$

$$\phi_f=12.76\frac{Rl}{P_1g}F_gF_{d1} \tag{11c}$$

$$\frac{1}{L_{ao}}=10^9\frac{i_{ao}}{\psi_{ao}}=\frac{10^8}{1.5P_1}\left(\frac{K_pK_dP_1}{N}\right)^2\frac{A}{\phi_f} \tag{11d}$$

$$\frac{1}{L_{ao}}=\frac{10^8}{19.14}\frac{A}{F_gF_{d1}}\frac{g}{Rl}\left(\frac{K_pK_dP_1}{N}\right)^2 \tag{11e}$$

$$19.14=1.5\times12.76=1.5\times4\times3.19$$
$$=1.5\times4\times0.4\pi\times2.54 \tag{11f}$$

Stator Synchronous Reactance, x_d. The stator synchronous reactance x_d can be obtained most easily by arbitrarily separating it into the components x_{ad} and (x_d-x_{ad}). The former is the reactance of armature reactance, and the latter, somewhat unfortunately, has been termed the "leakage" reactance.

Assume the stator windings sinusoidally distributed with three-phase currents i_{ao} flowing therein. At the instant when the resulting sine wave of armature magnetomotive force is in the direct axis, the fundamental flux per pole will be as given by equation 12a. The corresponding per-unit generated voltage is given by equation 12b; this is x_{ad} by definition.

$$\text{Fundamental flux per pole}=\frac{3.19}{g}\frac{4}{\pi}\frac{1.5Ni_{ao}}{K_pK_dP_1}A_{d1}\frac{2}{\pi}\frac{2\pi Rl}{P_1} \tag{12a}$$

$$x_{ad}=\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}\frac{A}{F_g}=k_{ad}\frac{A}{F_g} \tag{12b}$$

The quantity (x_d-x_{ad}) has been evaluated several times in the technical literature. The most accurate published expressions are probably equation 37 of Alger[8] and equation 4a of Kilgore,[9] and the reader is referred to these references. In both cases, this quantity has been termed the armature "leakage" reactance.

Field-Winding Reactance, X_{ffd}. With a current of one ampere flowing in the field winding, the flux per pole due to air-gap flux is given by equation 14a. The corresponding inductance in henrys for the entire field-winding circuit of P_1 poles is given by equation 14b.

$$\text{Flux per pole}=3.19\frac{N_{fd}}{g}\frac{2}{\pi}F_{do}\frac{2\pi Rl}{P_1} \tag{14a}$$

$$L_{ffd1}=12.76\times10^{-8}\frac{Rl}{g}N_{fd}{}^2F_{do} \tag{14b}$$

Let Ψ_b and Ψ_t be the effective permeance† of the pole-body and pole-tip "leakage" paths per axial inch of machine length per pole, respectively. The inductance in henrys of the field-winding circuit of P_1 poles due to the pole-tip and pole-body flux is given by equation 14c.

$$L_{ffd2}=3.19\times10^{-8}N_{fd}{}^2lP_1(\Psi_b+\Psi_t) \tag{14c}$$

The total inductance in henrys of the field-winding circuit is given by equations 14d, e. Introducing equation 10a gives the per-unit value of the field-winding reactance, equation 14f.

$$L_{ffd}=3.19\times10^{-8}N_{fd}{}^2P_1l\left[\frac{4RF_{do}}{P_1g}+(\Psi_b+\Psi_t)\right] \tag{14d}$$

$$L_{ffd}=10^{-8}N_{fd}{}^2P_1l\left[\frac{K_\phi\phi_f}{F_gl}+3.19(\Psi_b+\Psi_t)\right] \tag{14e}$$

$$X_{ffd}=k_{ad}K_\phi x_{ad}+3.19k_{ad}{}^2\frac{Al}{\phi_f}(\Psi_b+\Psi_t) \tag{14f}$$

Mutual Reactance Between Stator and Field Winding, X_{afd}. The fundamental flux per pole per ampere field-winding current is given by equation 15a. If sinusoidal distribution of the armature winding is assumed, the corresponding mutual inductance in henrys is given by equation 15b. Introducing equation 10a into equation 15b gives X_{afd} as shown in equation 15c.

$$\text{Fundamental flux per pole}=3.19\frac{N_{fd}}{g}\frac{2}{\pi}F_{d1}\frac{2\pi Rl}{P_1} \tag{15a}$$

$$L_{afd}=3.19\times10^{-8}\frac{N_{fd}}{g}F_{d1}\frac{4Rl}{P_1}\frac{N}{K_pK_d} \tag{15b}$$

$$X_{afd}=\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}\frac{A}{F_g}=k_{ad}\frac{A}{F_g}=x_{ad} \tag{15c}$$

Equation 15c illustrates a major advantage of the selected base-current ratio: X_{afd} and x_{ad} are numerically equal.

nth Additional-Rotor-Circuit Reactance, X_{and}. With one ampere in the nth additional rotor circuit, the average flux density in the air gap within the bars which bound the nth circuit is given by equation 16a. The corresponding inductance in henrys for the entire circuit of P_1 poles is given by equation 16b.

$$B_{ave}=\frac{3.19}{g}\frac{2}{\pi}D_{don} \tag{16a}$$

$$L_{gnnd}=12.76\times10^{-8}\frac{Rl}{g}D_{don}y_{nd} \tag{16b}$$

The inductance due to the bar-slot leakage flux is given by equation 16c. This expression neglects the small amount of leakage flux around the bars where they emerge from the pole body. Equa-

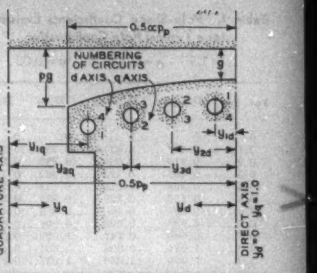


Figure 2. Pole and damper-bar dimensions and numbering of damper-winding circuits

y_d and y_q are measured in per unit of half the pole pitch ($0.5p_p$). y_{nd} and y_{nq} are the values of y_d and y_q, respectively, to circuit n, measured from and numbered from the corresponding (d or q) axis

* See "Results", reference 3.

† The permeance factor $(\Psi_b+\Psi_t)$ is difficult to evaluate and depends considerably upon the characteristics of the machine type being studied. Its complete derivation would be too long to be included in this paper. Satisfactory expressions have been given by Kilgore and Linville, and the permeance factor previously given is related to the corresponding quantities of Kilgore and Linville as follows:

$3.19(\Psi_b+\Psi_t)=\lambda_{Fs}+\lambda_{Fe}=L_3+L_4$

wherein λ_{Fs} and λ_{Fe} are evaluated in equations 15a and 16a of Kilgore, and L_3 and L_4 are evaluated in equation 14a of Linville.

tion 16c assumes that the slots are in open round slots as shown in the nomenclature; for rectangular slots, the factor 0.625 within the bracket should be replaced by $(0.333\, d_{sr}/w_{sr})$; for closed slots, the bracketed expression should be replaced by test or estimated values of the slot permeance.

$$L_{bsnd}=6.38\times10^{-9}P_1 l\left(\frac{d_r}{w_r}+0.625\right) \qquad (16c)$$

The inductance due to the end-ring leakage flux can be approximated by considering the end rings as two wires of a single-phase transmission line with a distance between centers of D_g and an (effective) cross-sectional radius of r_e. This inductance is given by equation 16d.

$$L_{esnd}=0.508\times10^{-8}P_1 l_{end}\left(9.2\log_{10}\frac{D_g}{r_e}+1\right) \qquad (16d)$$

The per-unit values of equations 16b, c, d, based upon the base-current ratio 10b, are given by equations 16e, f, g respectively.

$$X_{gsnd}=\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)^2\frac{A}{F_g}\frac{D_{d1n}}{F_{d1}}\gamma_{nd} \qquad (16e)$$

$$X_{bsnd}=0.5\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)^2\frac{A}{F_g}\frac{P_{1g}}{F_{d1}R}\left(\frac{d_r}{w_r}+0.625\right) \qquad (16f)$$

$$X_{esnd}=0.04\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)^2\frac{A}{F_g}\frac{P_{1g}}{F_{d1}R}\frac{l_{end}}{l}\times\left(9.2\log_{10}\frac{D_g}{r_e}+1\right) \qquad (16g)$$

The per-unit reactance of the nth additional rotor circuit is given by equation 16h.

$$X_{snd}=X_{gsnd}+X_{bsnd}+X_{esnd} \qquad (16h)$$

Mutual Reactance Between Stator and nth Additional Rotor Circuit, X_{sad}. With one ampere flowing in the nth additional rotor circuit, the maximum value of the fundamental component of flux density is given by equation 17a, and the mutual inductance in henrys between the stator and the nth additional rotor circuit is given by equation 17b.

$$\beta_{fsnd}=\frac{3.19}{\ell}D_{d1n} \qquad (17a)$$

$$L_{snd}=12.76\times10^{-8}\frac{Rl}{P_{1g}}\frac{N}{K_w K_d}D_{d1n} \qquad (17b)$$

If the base-current ratio 10b is used, the per-unit mutual reactance corresponding to equation 17b is given by equation 17c.

$$X_{sad}=\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)\frac{A}{F_g}\frac{D_{d1n}}{F_{d1}}=\frac{D_{d1n}}{D_{d1z}}x_{ad} \qquad (17c)$$

Note that with the base-current ratio 10b, the mutual reactance X_{sad} becomes numerically equal to x_{ad} for the xth additional rotor circuit.

Mutual Reactance Between Additional Rotor Circuits, X_{nkd} $(k>n)$. The mutual inductance L_{nkd} between the nth additional rotor circuit and any outer rotor circuit k is equal to the sum of L_{gsnd} and L_{esnd} since the fluxes which define the latter inductances are mutual with the outer circuit. L_{nkd} is therefore as given by equation 18a. The per-unit mutual reactance X_{nkd} of equation 18b is based on the base-current ratio 10b. X_{gsnd} and X_{esnd} are given by equations 16e and 16f, respectively. The mutual reactance between the nth additional rotor circuit and any inner circuit can be obtained from the impedances of the inner circuit, since all mutual impedances in this article are reciprocal.

$$L_{nkd}=L_{gsnd}+L_{esnd} \qquad (18a)$$

$$X_{nkd}=X_{gsnd}+X_{esnd}\quad (k>n) \qquad (18b)$$

Mutual Reactance Between Field-Winding Circuit and nth Additional Rotor Circuit, X_{nfd}. The mutual inductance L_{nfd} between the field-winding circuit and the nth additional rotor circuit is $N_{fd}L_{gsnd}$, since the flux which defines the latter inductance is mutual with the field-winding circuit. L_{nfd} is given by equation 19a, and the corresponding per-unit value, based on the base-current ratios equations 10a and 10b is given by equation 19b.

$$L_{nfd}=N_{fd}L_{gsnd}=12.76\times10^{-8}\frac{Rl}{\ell}D_{d1n}\gamma_{nd}N_{fd} \qquad (19a)$$

$$X_{nfd}=\left(\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}\right)\frac{D_{d1n}}{D_{d1z}}\gamma_{nd}x_{ad} \qquad (19b)$$

Stator Resistance, r_a. The stator resistance is a definitive impedance, and its per-unit value is given by equation 20a.

$$r_a=\frac{r_a}{z_{ab}} \qquad (20a)$$

Field-Winding Circuit Resistance, R_{ffd}. R_{ffd} is easily obtained from the design or name-plate data. The corresponding per-unit value, based on the base-current ratio 10a, is given by equation 21a.

$$R_{ffd}=\frac{10^8}{\omega P_1}\left(\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}\right)^2\frac{1}{N_{fd}^2}\frac{A}{\phi_f}R_{ffd} \qquad \text{(no external resistance)} \qquad (21a)$$

Table II. Comparison of Pole-Shape Coefficients Obtained in This Paper by Numerical Integration With Corresponding Values Obtained by Wieseman

$\rho=1.50\quad \alpha=0.70\quad p_p^{-1}g=0.03$

	A_{d1}	A_{q1}	F_{d1}	K_c
1	0.874	0.472	1.037	1.020
2	0.876	0.481	1.062	1.010

1 = values obtained in this paper by numerical integration.

2 = values obtained by Wieseman[5] from flux plots.

Resistance of nth Additional Rotor Circuit, R_{snd}. The resistance of the two bars which form the nth additional rotor circuit in each pole is given by equation 22a. The resistance of the corresponding end-ring section is given by equation 22b. The resistance of the entire nth additional rotor circuit of P_1 poles is given by equation 22c, and the corresponding per-unit value is given byequation 22d.

$$R_{bsnd}=1.67\times10^{-8}\frac{l_{bn}}{a_{bn}}P_1 \qquad (22a)$$

$$R_{esnd}=3.33\times10^{-8}\frac{l_{end}}{a_{end}}P_1 \qquad (22b)$$

$$R_{snd}=1.67\times10^{-8}P_1\left(\frac{l_{bn}}{a_{bn}}+2\frac{l_{end}}{a_{end}}\right) \qquad (22c)$$

$$R_{snd}=\frac{10^8}{\omega P_1}\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)^2\frac{A}{\phi_f}R_{snd} \qquad (22d)^*$$

Mutual Resistance Between Additional Rotor Circuits, R_{nkd} $(k>n)$. The mutual resistance between the nth additional rotor circuit and any outer rotor circuit k is the end-ring resistance of the nth additional rotor circuit. R_{nkd} is given by equation 23a, and the corresponding per-unit value by equation 23b. The mutual resistance between the nth additional rotor circuit and any inner rotor circuit is obtained from the latter, since in this article all the mutual impedances are reciprocal.

$$R_{nkd}=R_{esnd}=3.33\times10^{-8}\frac{l_{end}}{a_{end}}P_1 \qquad (23a)$$

$$R_{nkd}=\frac{10^8}{\omega P_1}\left(\frac{4}{\pi}\frac{A_{d1}}{D_{d1z}}\right)^2\frac{A}{\phi_f}R_{nkd} \qquad (23b)^*$$

Impedances of Quadrature-Axis Circuits

The currents in the additional rotor circuits in the quadrature axis are expressed in per unit of I_{zdo} which is the base current of the direct-axis additional rotor circuits. This base is adopted so that the per-unit currents in the direct- and quadrature-axis additional rotor circuits may be added directly.

The concept of a field winding in the quadrature axis appears academic, but it is convenient to assume such a winding (but of infinite resistance), with a base current defined analogously to I_{fdo}. By this concept the stator flux which is leakage with respect to all the rotor circuits is (x_q-x_{ad}) for both the direct and quadrature axis. In addition, the assumption of the existence of a quadrature-axis field winding is convenient, since it maintains symmetry between the direct- and quadrature-axis equations.

The equations of the quadrature-axis circuits, including the quadrature-axis field winding, are identical with the direct-

*Equations 22d and 23b are evaluated for copper at 75 degrees centigrade. For any other material at/or any other temperature, these equations should be multiplied by the material resistivity in per unit of the resistivity of copper at 75 degrees centigrade.

axis equations with the d replaced by q. It would appear therefore that the formulas for the quadrature-axis impedances could be obtained from the corresponding direct-axis formula by merely substituting q for d. This is actually true for the ampere-inch-second values (ohms and henrys), but is not true for the per-unit values because I_{sdo} is the base current for the additional rotor circuits in both axes. The per-unit quadrature-axis impedances are obtained by substituting q for d in the corresponding direct-axis ampere-inch-second impedance formula, and converting the result into a per-unit value based on the base-current ratio 10b.

Stator Synchronous Reactance, x_q. x_q is evaluated by separating it into the two components x_{aq} and $(x_q - x_{aq})$ analogously to the method used in the evaluation of x_d. x_{aq} is given by equation 24a. $(x_q - x_{aq})$ is independent of the rotor position and is equal to $(x_d - x_{ad})$.

$$x_{aq} = \frac{4}{\pi}\frac{A_{g1}}{F_{g1}}\frac{A}{F_g} = \frac{A_{g1}}{A_{d1}}x_{ad} \tag{24a}$$

$$x_q - x_{aq} = x_d - x_{ad} \tag{24b}$$

nth Additional-Rotor-Circuit Reactance, X_{snq}. The components of L_{snq} can be obtained from the corresponding components of L_{snd} by substituting q for d. If the base-current ratio 10b is used, the corresponding per-unit values are given by equations 25a, b, c. The total reactance X_{snq} is given by equation 25d.

$$X_{gnnq} = \left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)^2\frac{A}{F_g}\frac{D_{gqn}}{F_{g1}}y_{nq} \tag{25a}$$

$$X_{bnnq} = 0.5\left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)^2\frac{A}{F_g}\frac{P_1 g}{F_{g1}R}\left(\frac{d_r}{w_r}+0.625\right) \tag{25b}$$

$$X_{snnq} = 0.04\left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)^2\frac{A}{F_g}\frac{P_1 g}{F_{g1}R}\frac{l_{enq}}{l}\times\left(9.2\log_{10}\frac{D_g}{r_g}+1\right) \tag{25c}$$

$$X_{snq} = X_{gnnq}+X_{bnnq}+X_{snnq} \tag{25d}$$

Mutual Reactance Between Stator and nth Additional Rotor Circuit, X_{snq}. L_{snq} can be obtained from equation 17b by substituting q for d. The corresponding per-unit value, based on the base-current ratio 10b, is given by equation 26a.

$$X_{snq} = \left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)\frac{A}{F_g}\frac{D_{gqn}}{F_{g1}} = \frac{D_{g1n}}{D_{g1x}}x_{aq} \tag{26a}$$

Mutual Reactance Between Additional Rotor Circuits, X_{nkq} $(k>n)$. In a manner similar to that used in the derivation of X_{nkd} it can be shown that X_{nkq} is given by equation 27a.

$$X_{nkq} = X_{gnnq}+X_{snnq} \quad (k>n) \tag{27a}$$

Resistance of nth Additional Rotor Circuit, R_{snq}. R_{snq} as given by equation 28a is obtained from equation 22c by substituting q for d. The corresponding per-unit value, based on the base-current ratio 10b, is given by equation 28b.

$$R_{snq} = 1.67\times10^{-9}P_s\left(\frac{l_{bn}}{a_{bn}}+2\frac{l_{enq}}{a_{enq}}\right) \tag{28a}$$

$$R_{snq} = \frac{10^8}{\omega P_1}\left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)^2\frac{A}{\phi_f}R_{snq} \tag{28b}*$$

Mutual Resistance Between Additional Rotor Circuits, R_{nkq} $(k>n)$. R_{nkq} as given by equation 29a is obtained from equation 23a by substituting q for d. The corresponding per-unit value, based on the base-current ratio 10b, is given by equation 29b.

$$R_{nkq} = R_{snnq} = 3.33\times10^{-4}\frac{l_{enq}}{a_{enq}}P_1 \tag{29a}$$

$$R_{nkq} = \frac{10^8}{\omega P_1}\left(\frac{4}{\pi}\frac{A_{g1}}{D_{g1x}}\right)^2\frac{A}{\phi_f}R_{nkq} \quad (k>n) \tag{29b}*$$

Appendix I. Evaluation of Pole-Shape Coefficients

The pole-shape coefficients D_{don}, D_{qon}, D_{g1n}, and D_{g1n} must be evaluated by flux plots if extreme accuracy is desired since the actual magnetic gap obviously cannot be represented exactly by any known mathematical expression. However, the flux-plotting method is too time-consuming to be used in the majority of actual problems. A more practical method is to obtain, by any means, whatsoever, a satisfactory mathematical expression for the gap permeance, and by means of numerical integration then evaluate the pole-shape coefficients. Such a method is used in this appendix.

The gap-reluctance expression by which satisfactory values of the pole-shape coefficients are obtained in this paper is given by equations 30a, b, . . . h; these expressions give the gap length in per unit of the minimum gap g.

$$g_y = g_d \text{ in the region } 0 < y_d < \alpha_q \tag{30a}$$

$$g_y = g_q \text{ in the region } \alpha_q < y_d < 1 \tag{30b}$$

$$g_d = 1+(\rho-1)\left(\frac{y_d}{\alpha}\right)^2 \tag{30c}$$

$$g_q = g_q+\beta g_q\sin^2\left(\frac{y_d-\alpha_q}{1-\alpha_q}\right)\frac{\pi}{2} \tag{30d}$$

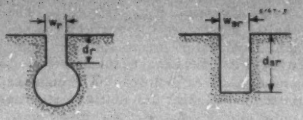
$$g_q = 1+(\rho-1)\left(\frac{\alpha_q}{\alpha}\right)^2 \tag{30e}$$

$$\beta = -1+\sqrt{1+\frac{1}{4}\left(\frac{1-\alpha}{p_p^{-1}g g_q}\right)^2} \tag{30f}$$

$$\alpha_q = \alpha-3.5pp_p^{-1}g \tag{30g}$$

$$y_d+y_q = 1.0 \tag{30h}$$

Figure 3. Rotor slots



D_{don}, D_{qon}, D_{g1n}, and D_{g1n} are defined in the following subsections, and definite-integral expressions for each are derived in terms of the reluctance expression 30a, b, . . . h. Numerical values obtained from these definite-integral expressions are given in Table I for a typical pole configuration.

Evaluation of D_{don}

$(2/\pi)D_{don}$ is defined as the factor by which the maximum gap density must be multiplied to obtain the average density within the damper circuit of span $2y_{nd}$ with the machine excited by the damper circuit of span $2y_{nd}$ in the direct axis. Expressing the corresponding flux per pole in the two ways shown by equation 31a leads directly to the evaluation of $D_{don}y_{nd}$ as given by equation 31b.

$$\phi = 2\int_0^{y_{nd}}\frac{3.19}{g g_y}dy_d = 2\frac{3.19}{g}\frac{2}{\pi}D_{don}y_{nd} \tag{31a}$$

$$D_{don}y_{nd} = \frac{\pi}{2}\int_0^{y_{nd}}g_y^{-1}dy_d \tag{31b}$$

Evaluation of D_{qon}

$(2/\pi)D_{qon}$ is analogous to $(2/\pi)D_{don}$ but in the quadrature axis. Its value as given by equation 32a is obtained by the same derivation as was used for D_{don}. The integral value given by equation 32b is obtained from equation 32a by changing the origin of integration by means of equation 30h.

$$D_{qon}y_{nq} = \frac{\pi}{2}\int_0^{y_{nq}}g_y^{-1}dy_q = \frac{\pi}{2}\int_{1-y_{nq}}^{1}g_y^{-1}dy_d \tag{32a, b}$$

Evaluation of D_{g1n}

D_{g1n} is defined as the factor by which the maximum flux density must be multiplied to obtain the maximum of the fundamental component of flux density with the machine excited by the nth additional rotor circuit in the direct axis. The flux density per ampere turn at any point along the gap can be written as in equation 33a; the maximum value of the fundamental component is then given by equation 33b. By the definition of D_{g1n}, the maximum value of the fundamental component can also be written as in equation 33c, and D_{g1n} can be evaluated as in equation 33d by equating expressions 33b and 33c.

$$\beta_y = \frac{3.19}{g g_y} \tag{33a}$$

$$\beta_{y\,fund} = 2\int_0^{y_{nd}}\frac{3.19}{g g_y}\cos\frac{\pi}{2}y_d dy_d \tag{33b}$$

$$\beta_{y\,fund} = \frac{3.19}{g}D_{g1n} \tag{33c}$$

$$D_{g1n} = 2\int_0^{y_{nd}}g_y^{-1}\cos\frac{\pi}{2}y_d dy_d \tag{33d}$$

*Equations 28b and 29b are evaluated for copper at 75 degrees centigrade. For any other material at/or any other temperature, these equations should be multiplied by the material resistivity in per unit of the resistivity of copper at 75 degrees centigrade.

Evaluation of D_{q1n}

D_{q1n} is analogous to D_{d1n}, but in the quadrature axis. Its value as given by equation 34a is obtained by the same derivation as was used for D_{d1n}. The integral value given by equation 34b is obtained from equation 34a by changing the origin of integration by means of equation 30h.

$$D_{q1n} = 2\int_0^{y_{nq}} g_y^{-1}\cos\frac{\pi}{2}y_q dy_q \qquad (34a)$$

$$D_{q1n} = 2\int_{1-y_{nq}}^{1} g_y^{-1}\sin\frac{\pi}{2}y_d dy_d \qquad (34b)$$

Appendix II. Accuracy of the Derived Pole-Shape Coefficients

It is obviously not possible at present to obtain complete checks on the accuracy of the foregoing integral expressions, because the necessary experimental information is lacking. If such information were available, the reluctance expression 30a, b, ...h would be unnecessary, since the pole-shape coefficients could be obtained directly from the experimental data. It is possible, however, to use the work of Wieseman as follows to check the accuracy of the limiting points $y_{nd}=1.00$, $y_{nq}=1.00$, and thereby obtain a qualitative estimate of the over-all accuracy.

Wieseman presented curves, based on actual flux plots, for the quantities A_{d1}, A_{q1}, F_{d1}, and K_ϕ. A check on the reluctance expression 30a, b, ...h, can be obtained by evaluating these same expressions by numerical integration based on equation 30a, b, ...h, and comparing these derived values with the corresponding quantities calculated by Wieseman. A_{d1}, A_{q1}, F_{d1}, and K_ϕ are defined in the following subsections, and definite-integral expressions for each are derived in terms of the gap-reluctance expression 30a, b, ...h. Numerical values as obtained from these definite integrals are given in Table II for a typical pole configuration and are there compared with the corresponding values obtained by Wieseman from flux plots. The agreement with Wieseman's results is sufficiently close as to warrant fully the use of the integral expressions for the pole-shape coefficients D_{d0n}, D_{q0n}, D_{d1n}, and D_{q1n} until absolutely accurate values can be obtained from actual flux plots.

Evaluation of A_{d1}

A_{d1} is defined as the factor by which the maximum flux density must be multiplied to obtain the maximum of the fundamental component of flux density with the machine excited by a sine-wave armature magnetomotive force in the direct axis. Assuming a sine-wave magnetomotive force of one ampere turn peak value in the direct axis, the flux density at any point in the gap is given by equation 35a, and the maximum value of the corresponding fundamental component of flux density is given by equation 35b. Based on the definition of A_{d1}, the maximum value of the fundamental component can also be written as in equation 35c, and A_{d1} can be evaluated as in equation 35d by equating expressions 35b and 35c.

$$\beta_y = \frac{3.19}{gg_y}\cos\frac{\pi}{2}y_d \qquad (35a)$$

$$\beta_{y\,fund} = 2\int_0^1 \frac{3.19}{gg_y}\cos^2\frac{\pi}{2}y_d dy_d \qquad (35b)$$

$$\beta_{y\,fund} = \frac{3.19}{g}A_{d1} \qquad (35c)$$

$$A_{d1} = 2\int_0^1 g_y^{-1}\cos^2\frac{\pi}{2}y_d dy_d \qquad (35d)$$

Evaluation of A_{q1}

A_{q1} is analogous to A_{d1} but in the quadrature axis. Its value as given in equation 36a is obtained by the same derivation as was used for A_{d1}. An alternative expression for A_{q1} in terms of y_d measured from the polar axis is given by equation 36b; this was obtained by substituting equation 30h into equation 36a.

$$A_{q1} = 2\int_0^1 g_y^{-1}\cos^2\frac{\pi}{2}y_q dy_q \qquad (36a)$$

$$A_{q1} = 2\int_0^1 g_y^{-1}\sin^2\frac{\pi}{2}y_d dy_d \qquad (36b)$$

Evaluation of F_{d1}*

F_{d1} is defined as the factor by which the maximum flux density must be multiplied to obtain the maximum of the fundamental component of flux density with the machine excited by the direct-axis field winding.

The field winding links only the flux which enters the pole, and its effective span or pitch is accordingly somewhat less than 100 per cent. However, the effective span is greater than the physical-pole arc, because the field winding links the flux which enters the side of the pole tip. Hence, the effective span of the field winding approaches but remains slightly less than the full 100-per-cent value. A study of Table I, however, shows that D_{d1n} is relatively constant (for given values of ρ, α, and $p_y^{-1}g$) for values of y_{nd} in the neighborhood of 1.00. Relatively little error is introduced therefore by assuming that F_{d1} is given by D_{d1n} for $y_{nd}=1.00$. Wieseman's values of F_{d1} thus may be compared directly with D_{d1n} for $y_{nd}=1.0$ as obtained in this paper by numerical integration.

Evaluation of K_ϕ

K_ϕ is defined as the factor by which the total fundamental flux per pole must be multiplied to obtain the total flux per pole, with the machine excited by the direct-axis field winding. By means of the previously justified assumption that the field-winding circuit is equivalent to a damper-winding circuit of 100-per-cent pitch (with negligible error), K_ϕ can be evaluated in terms of D_{d0n} and D_{d1n} for $y_{nd}=1.00$, as shown in the following.

By the definition of D_{d0n} and D_{d1n}, the total flux per pole and the total fundamental flux per pole are given by equations 37a, b, respectively, with y_{nd} taken as unity. The ratio of equation 37a to equation 37b then gives K_ϕ as in equation 37c, by definition.

*Wieseman called this quantity A_1.

$$\text{Total flux per pole} = \frac{3.19}{g}\frac{2}{\pi}D_{d0n} \qquad (37a)$$

$$\text{Fundamental flux per pole} = \frac{3.19}{g}\frac{2}{\pi}D_{d1n} \qquad (37b)$$

$$K_\phi = \frac{D_{d0n}}{D_{d1n}|_{y_{nd}=1.0}} \qquad (37c)$$

Nomenclature

The quantities given below are per-unit values unless in bold-face type in which case they are in the physical ampere-inch-second system (amperes, ohms, henrys, and so forth). Quantities such as N, P_1, R, l, for which it is obviously unnecessary to distinguish the ampere-inch-second values by a special script are in standard type only. Vector values are indicated by a circumflex ($\hat{}$) over the symbol.

All dimensions are in inches.

The subscript notation is as follows.

a, b, c = armature phases
f = field-winding circuit
n, k, x = damper-winding circuits. n is the general term; k refers to a damper-winding circuit external to n ($k>n$); and x refers to the 100-per-cent-pitch (most external) circuit which is used as a base
d, q, 0 = direct, quadrature, and "zero" axes
o = base quantities
m = order of harmonic

Only the direct-axis quantities are defined in the following, as the quadrature-axis quantities are obtained from these by merely substituting q for d.

a_{bn} = cross-sectional area of bar n
a_{end} = average cross-sectional area of end ring for bar n
A = flat-topped armature reaction at base stator current

$$A = \frac{1.5\hat{\imath}_{ao}N}{K_pK_dP_1}$$

A_{d1} = defined in Appendix II
D_{d0n}, D_{d1n} = defined in Appendix I
D_q = axial distance between end rings minus axial length of pole, or twice the distance between one end ring and side of pole
$\hat{e}_{ao}$ = peak value of rated stator phase voltage
E_{fd}, E_{nd} = rotor-circuit applied voltages
$F_{d0}=D_{d0n}$ for $y_{nd}=1.0$
F_{d1} = defined in B3
F_g = field-winding ampere turns for rated air-gap-line stator voltage
g = minimum gap, effective
g_y = gap length at any point y_d, in per unit of g
$\hat{\imath}_{ao}$ = peak value of rated stator line current
I_{fdo}, I_{xdo} = base-current; field winding, and xth additional rotor circuit, respectively
i_d, I_{fd}, I_{nd} = direct-axis currents; stator, field winding; and nth additional rotor circuit, respectively
I_n = total current in nth physical bar
$k_{ad}=\frac{4}{\pi}\frac{A_{d1}}{F_{d1}}$
K_p, K_d = pitch and distribution factors, respectively (greater than 1.0)

K_ϕ = defined in Appendix II

l = machine stacked length

l_{bn} = length of bar n

l_{end} = circumferential length of end ring measured from direct axis to center of bar n

L = ampere-inch-second inductance corresponding to per-unit reactance x

L_{ao} = base stator inductance

$$L_{ao} = \frac{10^{-8}\psi_{ao}}{i_{ao}} = \frac{x_{ao}}{\omega}$$

N = stator series turns per phase

N_{fd} = turns per pole of field winding

p = differential operator $= \dfrac{d}{d(\omega t)}$

p_p = pole pitch $= \dfrac{2\pi R}{P_1}$

P_1 = number of poles

r_a = stator resistance per phase

r_e = effective radius of end-ring cross section; $\pi r_e^2 = a_{end}$

R_{bnnd}, R_{ennd} = resistances of nth additional rotor circuit; bar and end ring, respectively

R_{ffd}, R_{nnd} = resistance of field-winding and nth additional rotor circuits, respectively

R_{nfd}, R_{nkd} = mutual resistances, nth additional rotor circuit to field winding and kth circuit, respectively

s = slip in per unit

$\hat{U}_{nbm}$ = current modulus defined in equation 9a

v = general rotor-velocity term of equation 4

z_{ao} = base stator ohms

$$z_{ao} = \frac{e_{ao}}{i_{ao}} = \omega L_{ao}$$

x_{ad} = reactance of armature reaction

x_d, X_{ffd}, X_{nnd} = direct-axis reactances; stator, field winding, and nth additional rotor circuit, respectively

X_{afd}, X_{and}, X_{nfd}, X_{nkd} = mutual reactances; stator field, stator–nth rotor circuit, nth rotor circuit to field winding, and nth rotor circuit to kth rotor circuit

X_{bnnd}, X_{ennd}, X_{gnnd} = reactance components of nth rotor circuit; due to bar-slot flux, end-ring flux, and air-gap flux, respectively

$z_d(p)$ = operational stator impedance as viewed from stator terminals

y_d, y_r = peripheral distances on pole face measured in per unit of half the pole pitch; see Figure 2

α = ratio of pole arc to pole pitch

β'_{max} β'_{tnnd} = maximum flux density and maximum value of the fundamental component of flux density at normal voltage no load

ρ = ratio of maximum gap to minimum gap; see Figure 2

ϕ_f = fundamental flux per pole at normal voltage no load

ψ_{ao} = peak value of rated stator phase linkages; $a_{ao} = 10^{-8}\omega_{ao}$

ψ_d, Ψ_{fd}, Ψ_{nd} = direct-axis linkages; stator, field-winding, and nth additional rotor circuits, respectively

Ψ_l, Ψ_l = effective permeance of the pole-body and pole-tip leakage paths per axial inch of machine length per pole

Modern Practice in Power-Plant Auxiliary Equipment and Systems

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THIS DISCUSSION of central-station auxiliary equipment and systems cannot cover the entire field of practice, but must touch only selected high spots. The particular points selected were chosen to include those items where the user may exercise judgment in choosing alternate arrangements of supply or items of apparatus, or where his specifications may influence apparatus design by emphasis on particular requirements.

The discussion is timely, because power-plant auxiliary equipment has undergone important development in the past several years, and because the interruption in normal construction of new facilities, necessitated by war activities, provides an opportune moment for analysis of what is available and how to apply it.

Supply systems for auxiliaries have received extensive study with the result that loop and network systems now find application along with the more conventional radial distribution system. The change in equipment is keynoted by the swing to air circuit breakers and the currently marked trend toward the use of air-cooled transformers. Both motors used for central-station auxiliary service and the associated motor starters have been given close attention with the general result that more economical reliable drives will be available to meet rigid requirements. One fact is ever apparent: the central-station operator demands maximum reliability. Nowhere else on the entire power system is the requirement of reliability so great compared to the investment in equipment involved.

There follows, thus, a discussion of particular design features of motors, desirable arrangements of switchgear and control, and data on distribution systems that may be helpful when selection of the method of supply is under consideration.

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Motor Design

As in the past, the squirrel-cage induction motor for across-the-line starting is the best selection for an auxiliary drive wherever constant-speed operation is desired. The simplicity, reliability, and low cost all enter to make it the number-one choice. Its control is simple as well. The higher power factor and efficiency of synchronous drives is offset by the increased complication of synchronizing control and a source of excitation. Also, since the cost of both real and reactive power is a minimum at the generator bus, higher efficiency and power factor is not a large incentive.

Rotor Design

Draft fans and some pulverizers have high inertia, and motors for these loads are best designed to limit the temperatures and expansion of the rotors to safe values. The WR^2 of each drive of this nature should be supplied to the motor designer for an analysis of the particular application. Certain types of pulverizers are subject to jamming, and it is known from experience that operators may try several times to start them. Motors for these pulverizers require an extra margin in rotor thermal capacity. An ample air gap is especially desirable for motors on

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these two types of loads because of rotor expansion and should not be discouraged by unnecessary emphasis on high power factor. Similarly, adequate thermal capacity with ample starting torque may require higher starting current than might be obtained with a less reliable design, and unnecessary restrictions in this respect should not be imposed. Motors for high-inertia loads also should be designed to withstand the high transient torque which occurs when the motor is energized.

Another consideration which affects reliability but does not appear on the performance sheet is magnetic stability. This requires a satisfactory relation between the stiffness of the shaft and the unbalanced magnetic pull which occurs when the rotor is displaced radially with respect to the stator. Such displacement may be either deflection of the shaft and other structural parts caused by vibration or an initial displacement caused by machining tolerances. Here again an ample air gap is required for a reliable motor.

Insulation of Windings

The insulation of motor windings for central-station auxiliary service should be highly resistant to moisture, coal dust, and fly ash. Although the atmospheric conditions are no more severe than in many industrial plants, the extreme importance of reliability of the auxiliaries requires the best possible insulation job. The smaller motors should be given ample varnish dips and bakes with carefully controlled viscosity and temperature, and the larger motors should be impregnated by the vacuum-pressure method. Mica insulation is to be used where practicable. The insulation between turns should be tested by a high-frequency testing set in addition to the conventional high-potential tests between the winding and ground.

Insulating materials good for higher temperatures and adverse moisture conditions have been written about widely during the last year. These are silicone varnishes that are now available in forms similar to the usual varnishes used by the electrical industry. They have been used with mica, glass, and asbestos to produce high-temperature insulations. The improved thermal endurance can be utilized in a number of important ways in the design of electric equipment, such as reduction in size and weight, increased service life for conventional size and weight, and operation in ambient temperatures beyond the limits permissible for usual types of insulation. A few cases of power-plant operation may justify trial of silicone insulations. One likely application is for motors driving induced-draft fans subject to high ambient temperatures.

At the present time quantities of silicone products are limited, and their cost is high compared to good insulating varnishes. Much is still to be learned about processes of handling and manufacturing that will have to be studied before application to motor equipment becomes general.

Motor Bearings

Both antifriction and sleeve-type bearings are furnished today. Each type has its advantages and consequently is to be preferred for certain applications. The sleeve bearing has advantages for many general applications. It requires less precision work both in manufacture and maintenance, it inherently is suitable for operation in locations where coal dust and fly ash are present, and it can be operated at higher peripheral speeds. The antifriction bearing may find preference because of smaller space requirements, because of its ability to take thrust loads, or because of the low starting friction inherent to its design. This last point refers particularly to vertical pump motors where heavy thrust is encountered. Prelubricated ball bearings are now used on some small motors. This practice stands to become more popular since field experience with it has been excellent. These bearings have shown unusual freedom from trouble.

Boiler-feed-pump motors generally are connected to the load through flexible couplings. Certain of these couplings have a natural tendency to lock into a fixed running position while transmitting torque, thus preventing the motor and pump from moving axially with respect to each other. Because of shaft expansion which results from high-temperature operation of the pump in handling feed water, heavy thrust can be imposed upon the motor bearings. Failure of these bearings may result, since this thrust is beyond the capacity of simple sleeve-bearing shoulders. Occurrence of such phenomena can be prevented if the "limited end-float" type of coupling and a motor having shaft end play more than the end play of the coupling is specified.

Noise Level of Motors

Although the noise level in different power plants may vary somewhat, an average figure can be taken to be about 100 decibels in the general vicinity of the turbine and principal auxiliaries. If the noise level of motors is to be kept to a value that will not contribute seriously to powerhouse noise, it is logical to assume that no motors should have a level as high as 100 decibels.

The greatest source of noise in large high-speed motors is windage and the siren effect resulting from jets of air from the rotor vent ducts. A system of axial-flow surface cooling of the rotor is used today that effectively reduces noise level on the very large two-pole motors. Figure 1 illustrates the construction of a large 3,600-rpm motor employing this type of design. Careful selection of slot combinations in the stator and rotor will reduce noise in addition to keeping stray loss and parasitic torques to a minimum.

Adjustable-Speed Drives

There are several auxiliaries which require adjustable-speed drives. Cranes, coal bridges, and similar material-handling equipment can be driven best by wound-rotor induction motors. The most suitable electric drive for stokers is a series variable-voltage a-c–d-c drive. Boiler-feed pumps are usually driven at constant speed, but when speed adjustment is desired a wound-rotor induction motor with a multipoint drum furnishes adequate control.

Adjustable speed is very desirable for draft-fan drives in order to reduce losses and erosion. Two speeds can be obtained with a pole-changing squirrel-cage motor, and this combination is used frequently with inlet-vane control. Thirteen or 20 speed steps can be obtained with a wound-rotor motor and drum, but this still requires the use of dampers or vanes for continuous control of gas flow. A squirrel-cage motor with a hydraulic coupling gives continuous speed control over about a four-to-one range. The coupling requires cooling water and involves extra bearings. Electric couplings do not require cooling water and give ten-to-one speed range but involve extra bearings,

Figure 1. Cutaway view of 3,600-rpm squirrel-cage induction motor

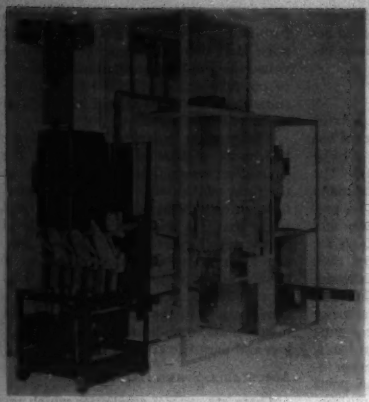

Figure 2 (left). Cell and air breaker for 2,300-volt auxiliary feed (five-kilovolt insulation, 150,000-kva interrupting capacity)

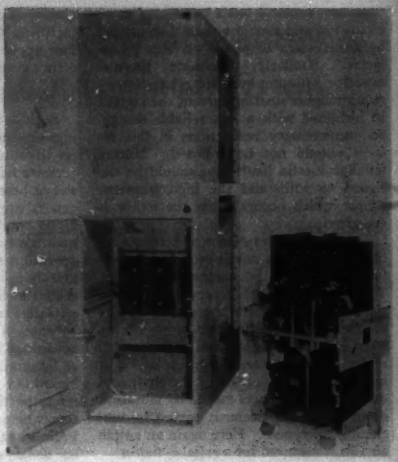

Figure 3 (right). Cell and air breaker for 600 volts or below; breaker shown is 800-ampere unit

an excitation system, and relatively high operating temperatures. A wound-rotor motor with a new type of liquid rheostat for secondary control has been used recently for large draft fans. This combination provides three-to-one speed range. It requires cooling water and an electrolyte, but eliminates extra bearings and rotating apparatus. The liquid rheostat appears to offer an attractive solution for future application.

The cost and efficiency of all of the afore-mentioned drives are comparable, so that the choice of drive should be made primarily to give maximum reliability with the particular operating conditions which will be encountered.

Switchgear and Control

As pointed out in the introduction, reliability is the outstanding qualification for all central-station auxiliary devices, and switchgear is no exception. Safety of operation, ease of installation, ease of maintenance, and so forth, are all important qualifications desirable here, just as in other classes of service, but dependability is paramount. Circuit breakers, contactors, fuses, and assemblies of these component parts all stress this virtue.

Metal-Clad Gear

These requirements all are met by up-to-date metal-clad gear in its various forms. The service record of metal-enclosed gear is enviable, and the manufacturers continue to make improvements in the breakers, housings, and other parts. Purchasers of metal-enclosed switchgear can rely on receiving the benefits of all new developments promptly.

All breaker and auxiliary units are arranged for line assembly. They can be throat-connected to liquid-cooled transformers or supplied as part of an integral structure with air-cooled transformers. These unit substation arrangements form a most satisfactory assembly of transforming and distributing apparatus. Switchgear structures, or the switchgear portion of unit substations, can be shipped fully assembled or in groups as large as the purchaser's handling equipment can accommodate. This usually saves considerable installation cost. Factory connections on control wiring are not disturbed, so that tests need not be repeated.

The reliability of metal-clad switchgear is now so well recognized that double-breaker arrangements for load circuits seldom are considered necessary, and even auxiliary or transfer busses are not common. Special circuits may have double feeds, usually from different breaker groups, but duplication of breakers beyond this is not often justified. Where motors may require frequent starting, air breakers in metal-clad gear are well suited for this service. Duplicate power supply or normal and alternate power supply to auxiliary busses with automatic transfer is frequently provided. Relays for this function and for other normal protective functions are mounted on the gear. Relays are preferably of the Flexitest type with removable elements and built-in test switches. Functioning of all such control circuits is tested at the factory.

Switchgear for service voltages below 600 is now usually supplied with drawout breakers which have safety interlocking features similar to those in high-voltage metal-clad switchgear. Increased use and improved manufacturing methods have brought the prices of drawout gear so close to the equivalent enclosed breakers with fixed mountings that the advantages of the removable breaker types easily justify the difference.

Low-voltage metal-clad switchgear is well suited for distributing power in radial, loop, or low-voltage network circuits. Standard units are available which contain the limiters and loop-circuit disconnecting switches when the switchgear is part of a network system. The flexibility with which the various units can be grouped permits arranging the limiter sections and supply circuits wherever they best tie in with the plant distribution system. The network breakers which are used in network systems may be mounted on the transformers or in a unit of the switchgear assembly.

Unit substations and power centers, usually with air-cooled transformers, form the most modern arrangement for supplying low-voltage power. These assemblies also may include high-voltage gear if the plant distribution system makes this arrangement desirable. The transformers used in network distribution arrangements also can be provided as parts of unit substations or power centers. A coordinated housing is provided which gives good uniform over-all appearance and full accessibility to the transformers and switchgear.

Air Circuit Breakers

Air circuit breakers virtually have replaced oil for power-plant auxiliary work. The switchgear for central-station auxiliary service is built around air breakers, in practically all ratings up through the 15,000-volt class. Various forms of high-voltage air breakers have been used since 1929, and all have given satisfactory operation. Their reliability has been definitely proved. The many advantages of air interruption, particularly for this service, are well recognized, and consequently they are usually included today in the purchaser's specifications.

Figure 2 shows a typical five-kilovolt removable unit, 150,000-kva interrupting capacity, equipped with its own wheels

for movement outside the steel cell. Units of five-kilovolt insulation class (for 2,300-volt auxiliary service) with 60-cycle test of 25 kv and impulse test of 60 kv are supplied in interrupting ratings up to 150,000 kva and in current ratings up to 2,000 amperes. These ratings adequately cover the larger central-station auxiliary field.

The low-voltage breakers are available in all ratings to cover the necessary application to central-station auxiliary drives. Interrupting ratings at 600 volts go as high as 100,000 amperes, and current ratings as high as 6,000 amperes at this highest interrupting rating. Figure 3 shows an electrically operated 800-ampere removable breaker and cells for 600-volt application.

Low-voltage breakers often are applied on the cascade principle, an arrangement which permits the lower breakers in the series to open fault currents in excess of their interrupting rating. This is permitted on the basis that the main or group breakers shall be free to open instantaneously to assist the smaller breakers in the interruption. It is obvious that such an arrangement does not provide selective tripping and that feeder circuits other than the one in trouble may be deenergized.

The standard duty cycle is not possible with breakers applied in cascade arrangements, and it is necessary that they be inspected before being reclosed if they have opened currents above their interrupting ability. This is indicated by the breaker next higher in the cascade having opened to assist in clearing the fault.

Because of the limited selectivity which exists in cascaded circuits, the application of this arrangement in central-station auxiliary service seldom will be found satisfactory. It usually will be necessary to make breaker applications in the same way that they are made with high-voltage circuits, with all interrupters of adequate capacity for the faults to which they will be subjected. This will frequently mean that the cost of breakers for a given installation will be somewhat more, but it is the only way in which the essential full selective tripping on faults can be obtained. On nonessential auxiliaries, cascaded arrangements might be considered, but in general their application in central-station auxiliary installations requires careful scrutiny.

Table I. High-Interrupting-Capacity Contactors

Air Break, 600 Volts and Below

Normal Eight-Hour Rating, Amperes	Interrupting Capacity, Rms Amperes	Maximum Horsepower Ratings	
		220 Volts	440–550 Volts
150	15,000	50	100
300	25,000	100	200
600	40,000	200	400

Currently, consideration is being given to mechanical timing as a means of coordinating breakers in series to avoid unnecessary tripping of circuits other than the faulted one, since breakers with means for instantaneous tripping will frequently go out simultaneously under heavy currents. Such co-ordinated timing is not permissible with cascaded breakers. All breakers in a time-coordinated scheme must have fully adequate interrupting capacity.

Contactors, Starters, and Fuses

There has been considerable discussion of the use of interrupters other than circuit breakers for protecting load circuits during high fault currents. High-interrupting-capacity contactors at 600 volts and below, of the air-break variety, are now available Typical ratings are shown in Table I.

The contactors listed in Table I are designed and rated in accordance with National Electrical Manufacturers Association Standards They are furnished with overload relays which provide thermal time-delay characteristics suitable for motor starting and protection in combination with instantaneous trip to take care of short-circuit conditions. The overload relays can be connected for alarm only on essential auxiliaries.

Still another idea has been receiving consideration to provide a motor starter which has a high interrupting capacity at a moderate cost. This is the combination of an oil-immersed contactor with overload relays and a current-limiting power fuse.

These starters may be applied safely to 2,300-volt circuits having a short-circuit capacity of 150,000 kva and to 4,600-volt circuits having a short-circuit capacity of 250,000 kva. They are available with either 100- or 200-ampere contactors. When determining the size of fuse to be used with a motor of a given rating it is necessary to give consideration to the locked-rotor current as well as the full-load current of the motor so that a co-ordinated design will result and the fuses will furnish the necessary short-circuit protection without blowing under ordinary motor starting conditions.

For essential circuits, such as most power-plant auxiliaries, it is believed that interrupting means that can be electrically or manually closed after fault clearing should be used. If an interrupter must be replaced after each short circuit, valuable time is lost that in the extreme case could be disastrous. For a few of the less essential auxiliary circuits, and particularly where short circuits are least likely to occur, the suggested combination starter can provide a very economical installation.

A blanket recommendation of this starter-and-fuse combination is impossible. Each case must stand on its own merits, or be discarded in favor of an air circuit breaker. If rapid restoration of service is of value in any given case, air breakers are dictated. If the available ratings of current-limiting fuses do not completely satisfy the individual requirements, breakers are again the answer. Central-station auxiliary service can be considered as the application requiring the utmost of dependability. As such, engineering and economics require very careful balancing before a decision to use the fuse and starter is reached.

Power-Distribution System

The radial system of power supply, studied carefully in many alternate forms, for decades has provided satisfactory service. It is characteristic of a radial system that the degree of reliability is somewhat proportional to its cost, and a high-performance system or a very skimpy system can be designed, depending upon just how far the engineer will go in sacrificing economics. The author believes that the more popular and time-proved forms of the radial system are well known to central-station operating men and that detailed description has no justified place in this discussion. Figure 4 pictures a typical radial system of supply to auxiliaries.

The Secondary Network for Powerhouse Supply

The application of a secondary network to auxiliary supply is rather novel, and detailed description, at least of the salient principles of application, will be included. The fact that central-station engineers have had a long-time knowledge of secondary networks for urban distribution has misled many when power-plant application is under consideration. The different forms that an auxiliary system network may take frequently are overlooked, since the engineer pictures only the city network and hence does not consider flexible arrangements applicable particularly to central-station auxiliary supply. Factors pertinent to the selection of a network system for auxiliary supply will be discussed.

The a-c secondary network system has

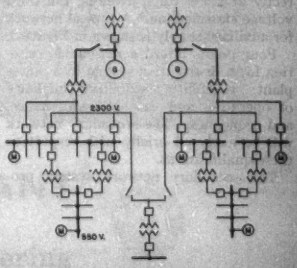

Figure 4. Radial distribution system for central-station auxiliary supply

been used for almost a quarter of a century in the commercial areas of some cities. Today there are 167 cities in the United States whose business districts are served by a-c secondary network systems, and this type of system is now recognized as the standard for serving heavy-load-density areas where the highest grade of service is required. During the last three or four years the advantages of the secondary network system have begun to be recognized in the industrial field, and the system has been installed in about 50 industrial plants. To date, however, the system has been used very little for supplying generating-station auxiliaries. One installation operating at 120/208 volts was made in a small station about eight years ago. Four installations operating at 460 volts have been made during the last four years. The performance of these five a-c secondary networks supplying generating-station auxiliaries has been up to expectations.

Each generating station is a separate problem requiring individual study. The network system for a plant may take the form of a grid, a loop, one or more spot network busses, or a combination of these. It is dangerous to generalize, but detailed studies on 12 stations ranging in size from 10 to 100 megavolt-amperes, indicate several things that are general enough to be of assistance in laying out a network for a particular power station.

First, in more than 50 per cent of the cases, a network grid will be more economical than a secondary loop or spot busses. Small stations are the exception to this rule. Next, a 460-volt grid is cheaper than a 208-volt network, except in very small stations. And also, unless maximum motor size exceeds 600 horsepower, all auxiliaries should be supplied from a 460-volt network. Motors above 600 horsepower should be supplied directly at 2,300 volts, or from a grid or spot networks at this voltage. The same primary windings are used for both the 2,300- and 460-volt networks. If 208 volts should prove economical in a small station, then all motors larger than about 50 or 75 horsepower should be served directly at 2,300 volts, avoiding the third voltage classification. A typical network for auxiliary supply is shown in Figure 5.

Four points afford a reasonable criterion for a distribution system in a power plant: reliability, flexibility, simplicity of operation and ease of maintenance, and economics. The secondary network will be analyzed briefly with respect to these qualifications.

The secondary network system provides maximum reliability and flexibility. The many years of experience with city network systems indicates that they are substantially as reliable as their source of supply and that they can be readily and economically expanded to take care of load growth. The network system is at least as simple as any type of system which will give somewhere near the same degree of reliability. The fact that any primary feeder together with its associated transformers can be removed from service without any interruption to service facilitates the operation, maintenance, and expansion of the system. Based on a number of careful economic studies, the investment cost of the network system has been found to vary from about 15 per cent more to about 14 per cent less than the cost of a radial system. In about 75 per cent of these studies the network system showed a saving of from 5 to 14 per cent. The result of any cost comparison will depend upon the form of network system used and the form of radial system with which it is compared. If lesser reliability is accepted, a radial system always can be designed that is the cheapest usable scheme. The foregoing figures refer to radial systems currently used and considered adequate.

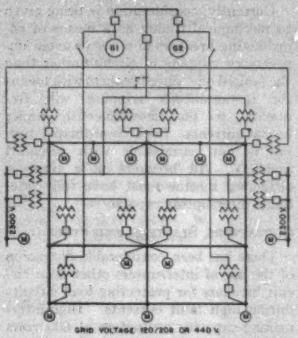

Figure 5. Secondary-network distribution system for central-station auxiliary supply

The matter of short-circuit current on a secondary network is something that must be watched in designing the system; otherwise the fault currents may run considerably higher than on a radial system, and the cost of the load circuit breakers will become excessive. The following are methods of keeping the interrupting duty on the load circuit breakers down.

1. Limit the amount of load on any one secondary grid or loop to a maximum of around 5,000 or 6,000 kva. This usually means a separate secondary grid or loop for each 100,000 kva of generating capacity or thereabouts, and less if small generators are involved and all load is supplied at low voltage.

2. Where necessary, two or more separate secondary grids or loops can be supplied from the same group of primary feeders The secondary networks preferably should be supplied over three or four primary feeders to keep the amount of spare-network transformer capacity to a small value.

3. The network transformers should have an inherent impedance of around ten per cent. This high impedance has the additional advantage of improving load division between the transformers supplying a network, and of minimizing circulating currents between primary feeders whose voltages may be slightly different in magnitude and phase angle.

4. If a spot network system is employed instead of a grid or loop form, the amount of load per spot bus should be kept down to 1,500 to 2,500 kva.

If the foregoing points are kept in mind as guides when a network system is being designed for supplying power to generating-station auxiliaries, the advantages of reliability, flexibility, and simplicity of this type of system usually can be obtained at less cost than those forms of radial system which will give somewhere near comparable reliability.

As stated, each generating station requires individual study. If the best system for a particular station is to be chosen, such study should be started early, before physical details of station design place limiting factors on the application of one type of system or the other. Whether new generation involves a new plant or simply additions to existing plant, of course affects the choice, although this fact is not necessarily limiting in itself.

Conclusion

In conclusion the author wishes to repeat that the foregoing paragraphs were selected as high lights, not as a general coverage on the subject of auxiliary apparatus and distribution systems. The selection of items and the discussion of them prove that central-station auxiliary performance will be improved through better supply-system layout and more reliable individual motors and control. It is sincerely hoped that the discussion may prove of help to central-station engineers when auxiliary apparatus specifications and auxiliary power-supply problems are under consideration.

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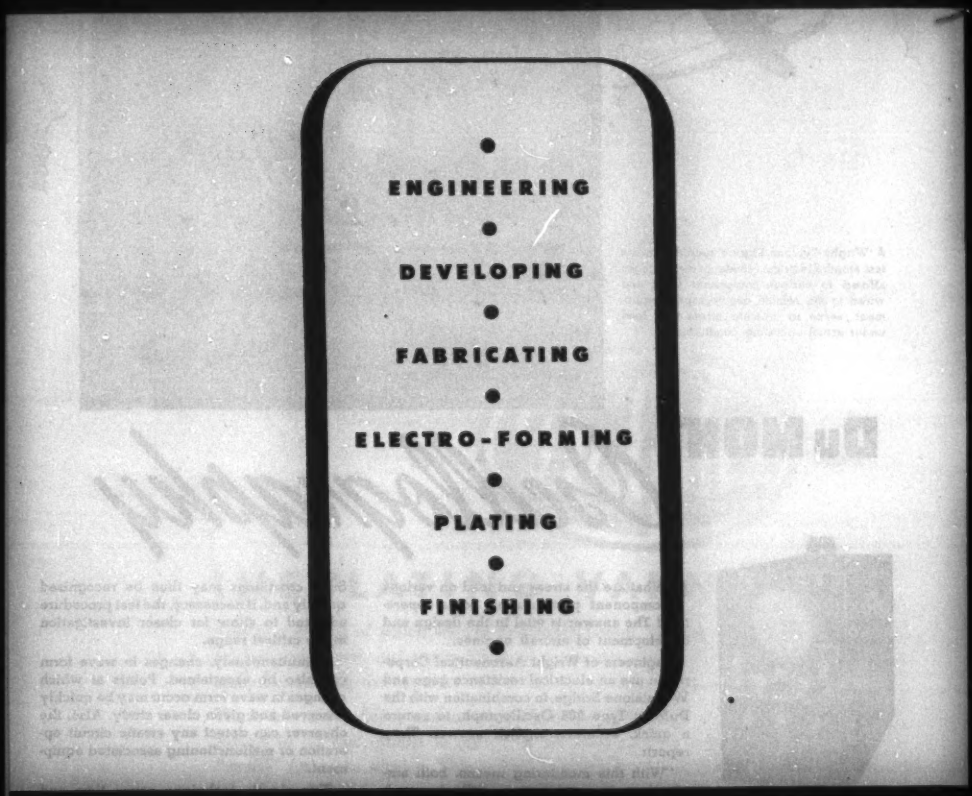

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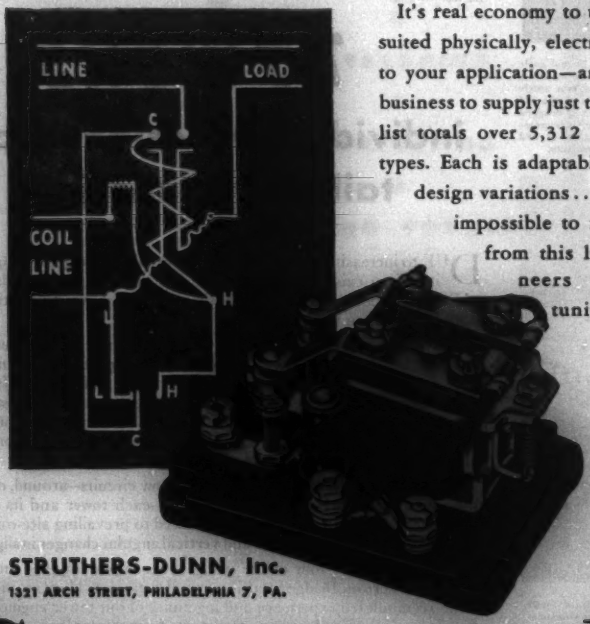

It's real economy to use relays that are *exactly* suited physically, electrically, and mechanically to your application—and it is Struthers-Dunn's business to supply just the unit you need. Today's list totals over 5,312 standard Struthers-Dunn types. Each is adaptable to numerous coil and design variations... but, should it still prove impossible to match your specification from this list, Struthers-Dunn engineers welcome the opportunity to "tailor" a new relay type to your exact measure.

A typical application of the Struthers-Dunn Type 88XX50 electrical lock-in relay used with a 3-wire "high-low" temperature control thermostat.

STRUTHERS-DUNN, Inc.
1321 ARCH STREET, PHILADELPHIA 7, PA.

STRUTHERS-DUNN

5,312 RELAY TYPES

DISTRICT ENGINEERING OFFICES: ATLANTA • BALTIMORE • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND • DALLAS • DENVER • DETROIT • HARTFORD • INDIANAPOLIS • LOS ANGELES • MINNEAPOLIS • MONTREAL • NEW YORK • PITTSBURGH • ST. LOUIS • SAN FRANCISCO • SEATTLE • SYRACUSE • TORONTO

Start RIGHT AND YOU End RIGHT!

with WESTONS ON ALL PRODUCTION TEST-STANDS AND INSPECTION EQUIPMENT!

With the race for markets in full swing, electrical manufacturers are eliminating costly production bottlenecks by providing *uniform dependability* in testing procedure all along the line. From the inspection of purchased components right through to final product inspection, they insure accurate testing by using instruments they can trust.

And it's easy to insure *measurement dependability* at every step, because there are WESTONS for every testing need . . . including types for all special test-stand requirements, as well as a broad line of multi-range, multi-purpose test instruments. These compact, multi-purpose testers often afford new simplicity and economies in testing procedure, while assuring the dependability for which WESTONS are renowned.

Literature describing the complete line of WESTON panel and test instruments is freely offered . . . Weston Electrical Instrument Corporation, 664 Frelinghuysen Avenue, Newark 5, New Jersey.

Weston *Instruments*

ALBANY • ATLANTA • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND • DALLAS • DENVER • DETROIT • JACKSONVILLE • KNOXVILLE • LOS ANGELES • MERIDEN
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Weston Electrical Instrument (Canada) Ltd., Montreal, Canada. Representative Overseas: Associated Electrical Industries, Ltd.

LABORATORY INSTRUMENTS FOR SPEED AND ACCURACY

TAILOR-MADE WAVES FOR RAPID TESTING

The *-hp-* Model 210A Square Wave Generator is designed to amplify and clip the tops of a sine wave, and thus convert it into a wave which has vertical sides and a flat top. When the square wave voltage is applied to the amplifier or network under test, the shape of the output wave immediately shows up any distortion.

In production testing, one or two observations with an *-hp-* Square Wave Generator will accurately check the frequency response. In development work, the *-hp-* Model 210A shows up phase shift and transient effects, both of which are difficult to study by other methods.

In practice, a wave which appears to be perfectly square will contain 30 or more harmonics; and when the amplitude or phase relation of the harmonics is disturbed, the square wave will be distorted. (See Fig. 1.) Thus the application of a square wave to a circuit shows up any irregularities in amplitude or phase transmission of that circuit, not only at the square wave frequency, but also at frequencies far removed from the test point. These characteristics are particularly important in television video amplifier work.

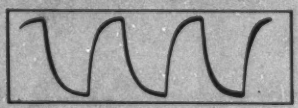


Fig. 1—Shows the square wave distortion caused by poor high frequency response

The output of the generator is square within 1 percent over the frequency range from 20 cps to 10,000 cps; a relatively square wave can be obtained even at 100 kc. The frequency response of the attenuator is sufficiently wide so that the output wave shape is not affected even at the highest frequencies. Once proper criteria have been established, the *-hp-* Model 210A Square Wave Generator is the modern, rapid means of production testing, with the speed and accuracy which are characteristic of all *-hp-* instruments.

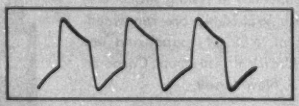


Fig. 2—Low frequency phase distortion serious in television video circuits

Write for complete details on the Model 210A. Ask for *-hp-* Catalog No. 17B, which includes much valuable information on development and measurements.

OTHER -hp- INSTRUMENTS

RESISTANCE-TUNED AUDIO OSCILLATORS

Require no zero setting . . . Several models available to cover frequency ranges from 2 cps to 200 kc.

NOISE AND DISTORTION ANALYZER MODEL 325B

Combines a vacuum-tube voltmeter with a set of fundamental elimination filters for general purpose measurements of total harmonic distortion, noise and voltage level.

VACUUM TUBE VOLTMETER MODEL 400A

Makes accurate voltage measurements from 10 cycles to 1 megacycle, covers nine ranges, (.03 volts to 300 volts) with full scale sensitivity.

HEWLETT-PACKARD COMPANY

BOX 1134 • STATION A • PALO ALTO, CALIFORNIA

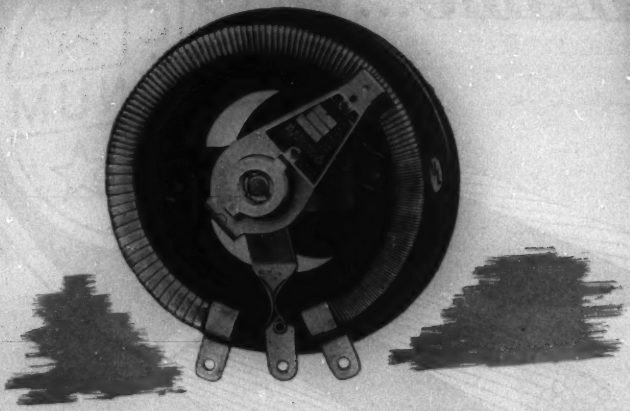
Audio Frequency Oscillators *Signal Generators* *Vacuum Tube Voltmeters*
Noise and Distortion Analyzers *Wave Analyzers* *Frequency Meters*
Square Wave Generators *Frequency Standards* *Attenuators* *Electronic Tachometers*

Alcoa can take care of your power conductor requirements for rural and hi-lines. Joints and other accessories for this construction are likewise available.

Aluminum Cable Steel Reinforced has the high strength and dependability required in modern line construction. Alcoa engineers will help you select conductors having suitable characteristics. Write ALUMINUM COMPANY OF AMERICA, 2149 Gulf Bldg., Pittsburgh 19, Pa.

ALCOA A-C-S-R

Smoother, Closer Control of Generator Voltage with OHMITE Field Rheostats



YOU get exact control *plus* permanently smooth operation . . . in a *compact* unit. The rheostats are tapered or uniformly wire-wound for separately or self excited generators. Continuous variation of resistance in even the smallest sizes saves control-panel space. This saving in space and weight is particularly valuable in portable equipment.

With a series of ten sizes from 25 to 1000 watts available in single or tandem units, there is an Ohmite Field Rheostat suitable for every small or medium size generator. Rheostats designed for special applications. Consult Ohmite engineers on your control problem.

SEND FOR HELPFUL CATALOG NO. 40

Write on company letterhead for this complete Catalog and Engineering Manual. Gives valuable data on rheostats, resistors, tap switches.

OHMITE MANUFACTURING COMPANY

4803 FLOURNOY STREET, CHICAGO 44, U.S.A.

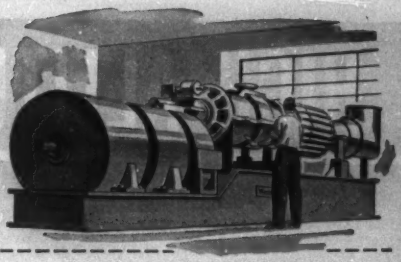
Foremost Manufacturers of Power Rheostats, Resistors, Tap Switches

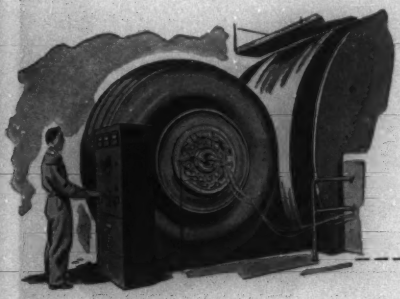
Be Right with OHMITE

RHEOSTATS • RESISTORS • TAP SWITCHES

In a laboratory a SCIENTIST experiments with a new gas turbine . . . using heat-resisting alloy blades that are far stronger, at 1100°F., than *ordinary* steel at room temperature.

. . . the name on the GAS TURBINE is Westinghouse.





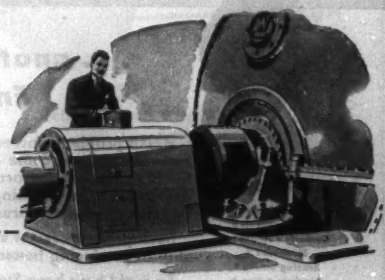
On a special machine a TESTER employs a Rototrol* for smoothly accelerating a large flywheel, used in determining the wear-resisting qualities of tires and brakes—for huge air transports of the future.

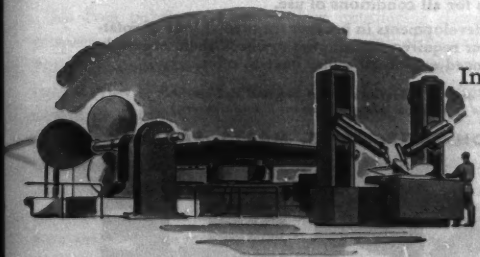
. . . the name on the ROTOTROL is Westinghouse.

*Registered Trademark

In a power plant an ENGINEER uses a Vibrograph to "take the pulse" of a turbo-generator . . . recording the smallest vibrations as a trace on a film.

. . . the name on the VIBROGRAPH is Westinghouse.





In a manufacturing plant an OPERATOR uses an electronic control to regulate the movement of milling cutters—for accurately machining irregular contours on giant ship propellers.

. . . the name on the ELECTRONIC CONTROL is Westinghouse.

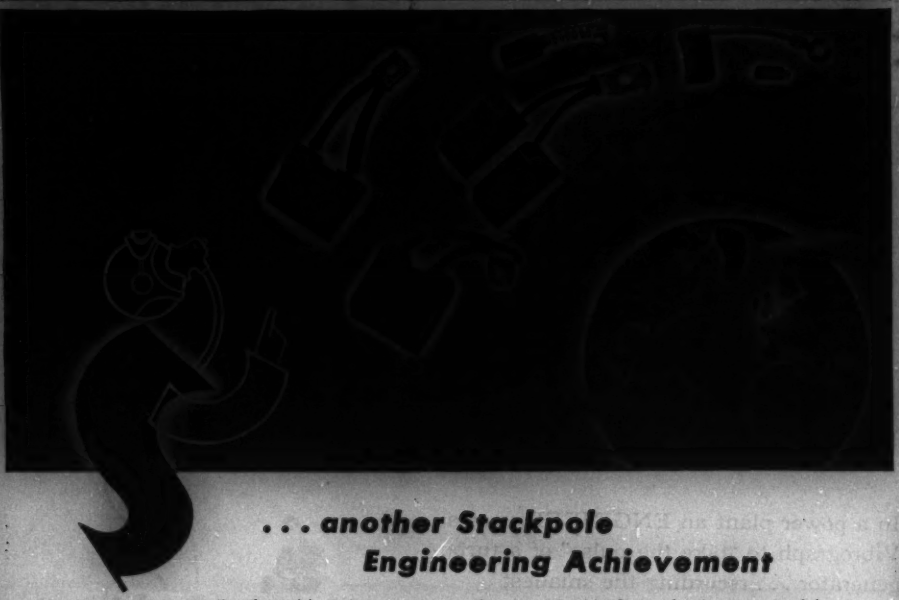
Westinghouse

PLANTS IN 25 CITIES OFFICES EVERYWHERE

NOW THAT Westinghouse technical skill and "know-how" have turned from war to peace, expect great things . . . from Westinghouse research, engineering, and precision manufacture.

Tune in: JOHN CHARLES THOMAS – Sunday, 2:30 pm, EST, NBC • TED MALONE—Mon. thru Fri., 11:45 am, EST, American Network

HIGH-ALTITUDE BRUSHES



. . . another Stackpole Engineering Achievement

OTHER STACKPOLE MOLDED PRODUCTS

Metal, Carbon, Graphite and Composition Contacts • Anodes • Electrodes • Brazing Blocks • Bearings • Pipe • Welding Rods, Electrodes, and Plates • Packing, Piston, and Seal Rings • Rheostat Plates and Discs • Resistors, etc.

Brush problems increase tremendously with altitude—and it has remained for Stackpole to overcome these by producing the first really outstanding brushes for high altitude performance. These brushes are treated with a special process developed by the Westinghouse Electric and Manufacturing Co., and have resulted in greatly increased brush life for high-altitude flying.

Such progress is not accidental. It is the natural result of long years of leadership in producing better brushes for all conditions of use.

So rapid have been Stackpole developments in brushes for many kinds of rotating equipment that, whatever your requirements, it pays to check them regularly against the latest types this advanced engineering may have to offer.

(Stackpole Brushes are sold only to manufacturers of original equipment. Replacements can be obtained from the original equipment manufacturers.)

STACKPOLE CARBON COMPANY, ST. MARYS, PA.

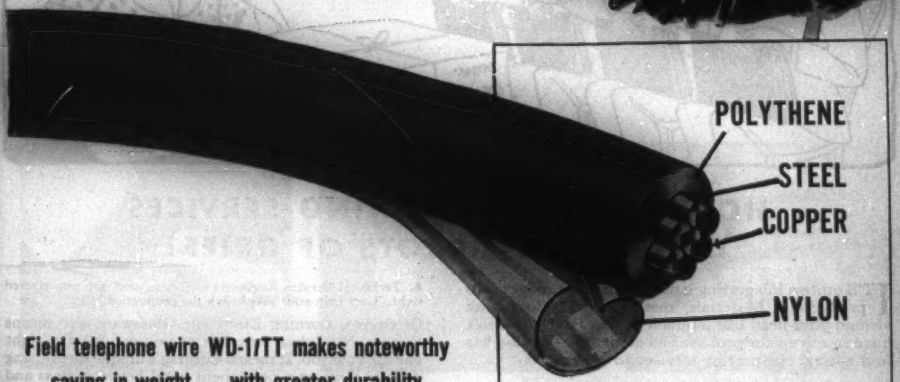
STACKPOLE *Brushes*

CARBON
CARBON-GRAPHITE
SILVER-GRAPHITE

FOR ALL TYPES OF
ROTATING EQUIPMENT

ELECTRO-GRAPHITE
COPPER-GRAPHITE
METAL COMPOSITION, ETC.

Insulated with
Du Pont POLYTHENE
Jacketed with
Du Pont NYLON



Section of Field Wire WD-1/TT, magnified approximately 12 times. Wall thickness of polythene insulation; 18 mils. Wall thickness of nylon jacket; 5-6 mils. Overall diameter; 80-82 mils. Average weight per mile: 48 lbs.

Field telephone wire WD-1/TT makes noteworthy saving in weight . . . with greater durability

Here's where *two* Du Pont plastics teamed up to fill a recent urgent need of the Signal Corps. Specifications called for a considerably lighter field telephone wire, which would possess the necessary durability as well as a talking range equal to that of the heavy Army field wire.

Du Pont polythene, because of its outstanding electrical properties, needs less weight to do a given job of insulation. Polythene alone is widely used as insulation on some of the lightest types of Army wire. But for this field wire it was necessary to protect the insulation against all kinds of weather, and abrasion from rocks, trees, sharp corners. That's where the toughness of nylon was called on to help. A wall thickness of only 5-6 mils of nylon, extruded rapidly over the polythene insulation, gave the necessary protection—and the finished wire weighs a little more than a third as much as the heavier type of Army field wire—though the talking range is the same.

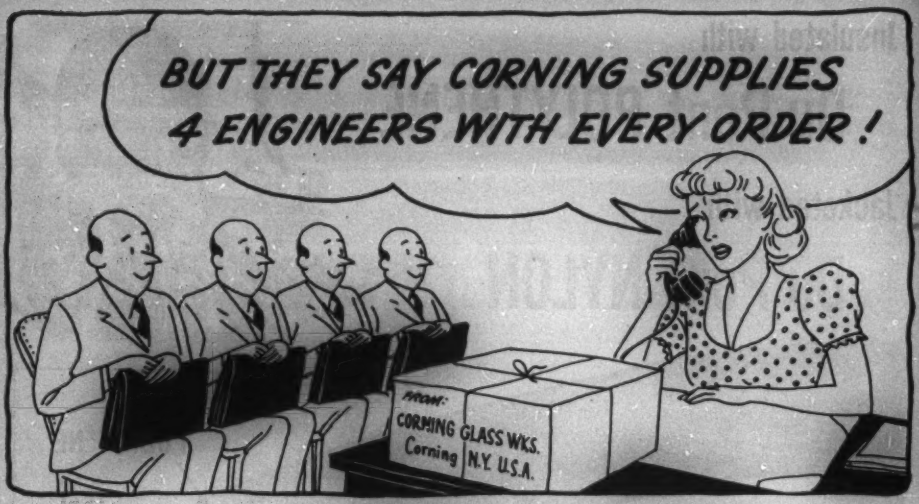
For information on nylon, polythene and other Du Pont plastics, write E. I. du Pont de Nemours & Co. (Inc.), Plastics Dept., Arlington, N. J.

FOR PLASTICS .. CONSULT DU PONT

DU PONT

BETTER THINGS FOR BETTER LIVING . . . THROUGH CHEMISTRY

Share in the Victory—Buy Bonds



HOW 4 SPECIAL CORNING SERVICES CAN SAVE YOU LOTS OF GRIEF!

IT'S quite a job getting a new electronic product into production. Materials, methods and prices buzz around your head like a bunch of bees. But you don't have to solve your problems all alone. For Corning has four special engineering services to help you:

1. Sales Engineers—To keep you in touch with latest developments and explain your problems to Corning's technical experts for prompt solution.

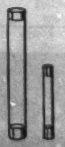
2. Product Engineers—Technical men who translate Corning Research in Glass into practical applications which may solve your particular headaches.

3. Plant Engineers—These men are anxious to see you get the best possible price on your order. They often point out changes in design which reduce costs.

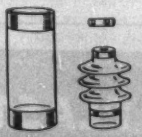
4. Technical Service Engineers — These men get you started right. They help your people lick the production bugs.

Of course, Corning Electronic Glassware also means thousands of glass formulae so you can get the right one for your job. It means Corning's unique metallizing process forming a permanent bond between glass and metal. Tubes, bushings, headers, etc., can be soldered in place to form permanent hermetic seals. It means an entire plant at Bradford, Pa., devoted exclusively to the manufacture of electronic specialties quickly, in large quantities. To get the fastest service in solving your pet problem, write, wire or phone Electronic Sales Department, N-12, Technical Products Division, Corning Glass Works, Corning, New York.

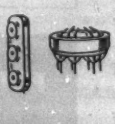
Note—The metallized Tubes and Bushings, Headers and Coil Forms below are all made by the famous Corning Metallizing Process. Can be soldered into place to form true and permanent hermetic seals. Impervious to dust, moisture and corrosion.



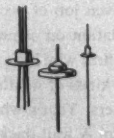
Metallized Tubes for resistors, capacitors, etc. 20 standard sizes ⅛" x 2" to 1¼" x 10". Mass-produced for immediate shipment.



Metallized Bushings. Tubes in 10 standard sizes, ⅛" x 1/16" to 1" x 4⅛" in mass production for immediate shipment.



Headers—The best way to get a large number of leads in a small space for assembly in one operation.



Eyelet Terminals—Single or multiple eyelets permit design flexibility. Standard items readily available in quantity.

Coil Forms—Grooved for ordinary frequencies—metallized for high frequencies. In various designs and mountings.

VYCOR Brand cylinders—very low loss characteristics. Stands thermal shock up to 900°C. Can be metallized.

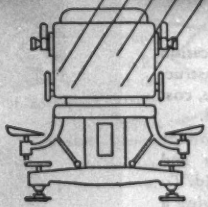
CORNING means Research in Glass

Electronic Glassware

VYCOR CORNING PYREX

"PYREX", "VYCOR" and "CORNING" *are registered trade-marks and indicate manufacture by Corning Glass Works, Corning, N. Y.*

Target practice with Relays and Keys



(Left to right) The operator punches the problem data on tape, which is fed into the computer. The solution emerges in the teletype receiver. Relays which figure out the problem look like your dial telephone system.

In designing the gun-control systems which shot down enemy planes, Army ballistic experts were faced by long hours of mathematical calculations.

So Bell Laboratories developed an electrical relay computer. It solved complicated problems more accurately and swiftly than 40 calculators working in shifts around the clock.

Resembling your dial telephone system, which seeks out and calls a telephone number, this brain-like machine selects and energizes electric circuits to correspond with the numbers fed in. Then it juggles the circuits through scores of combinations corresponding to the successive stages of long calculations. It will even solve triangles and consult mathematical tables. The operator hands it a series of problems with the tips of her fingers — next morning the correct answers are neatly typed. Ballistic experts used this calculator to compute the performance of experimental gun directors and thus to evaluate new designs.

In battle action, Electrical Gun Directors are, of course, instantaneous. Such a director helped to make the port of Antwerp available to our advancing troops by directing the guns which shot down more than 90% of the thousands of buzz bombs.

Every day, your Bell System telephone calls are speeded by calculators which use electric currents to do sums. Even now, lessons learned from the relay computer are being applied to the extension of dialing over toll lines.

BELL TELEPHONE LABORATORIES

EXPLORING AND INVENTING, DEVISING AND PERFECTING FOR CONTINUED IMPROVEMENTS AND ECONOMIES IN TELEPHONE SERVICE

THE CORRECT ANSWER TO YOUR RECTIFIER PROBLEM IS HERE

G-E Builds All Three

Selecting the rectifier best suited for a particular d-c application is not a decision that can be made on a "guess" basis. Construction, basic materials, operating characteristics, weight, size, cost and life expectancy are all factors that should be considered.

G.E. and only G.E. builds the three types of low-voltage rectifiers most generally used—copper-oxide, selenium and Tungar. All three are tops in quality and leaders in their field. To say that one type is better than another is as fatuous as saying a bomber is better than a fighter plane. Each performs best when doing the job for which it was specifically designed.

When blueprints call for rectifiers choose the correct size and type from the G-E line. If you're not sure of what is best for your need let G-E engineers help you. Years of experience qualify them to recommend the rectifier which will give you the most economical, most efficient and most reliable performance. Whether they recommend copper-oxide, selenium or Tungar you can be sure their selection is impartial because G.E. offers all three.

For more information write to Section A1255-32, Appliance and Merchandise Dept., General Electric Co., Bridgeport, Conn.

Hear the General Electric radio programs: "The G-E All Girl Orchestra" Sunday 10 p. m. EST, NBC. "The World Today" news every weekday 6:45 p. m. EST, CBS. "The G-E House Party" Monday through Friday 4:00 p.m. EST, CBS.

BUY VICTORY BONDS AND KEEP THEM

GENERAL ELECTRIC

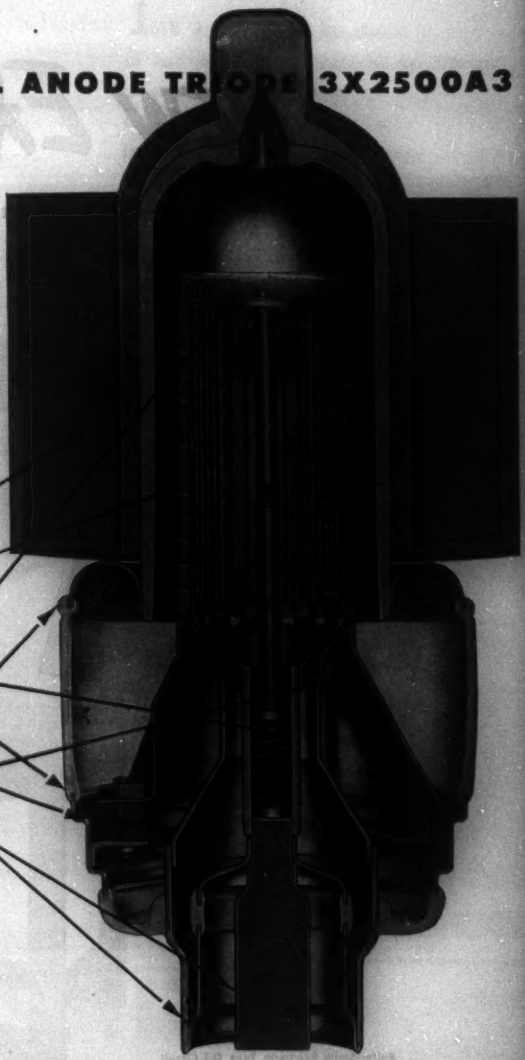
Eimac TUBES

THE COUNTERSIGN OF DEPENDABILITY IN ANY ELECTRONIC EQUIPMENT

NEW EIMAC EXTERNAL ANODE TRIODE 3X2500A3

Rugged mechanical construction
Outstanding electrical efficiency

In the new 3X2500A3, Eimac engineers have developed a highly efficient external anode triode which, in Class C service, delivers up to 5 KW output at a plate voltage of only 3,500 volts. The mechanical design is radically simple, incorporating a "clean construction" which gives short, low inductance heavy current connections that become an integral part of the external circuits at the higher frequencies.



The external anode, conservatively rated at 2500 watts dissipation, has enclosed fins so as to facilitate the required forced air cooling.

Non-emitting vertical bar grid does not cause anode shadows ordinarily created by heavy supports in the grid structure.

Thoriated tungsten filament. Note unusually large filament area, and close spacing.

Filament alignment is maintained throughout life of the tube by special Eimac tensioning method.

New glass-to-metal seals do not have the RF resistance common to iron alloy seals, nor the mechanical weaknesses of the feather-edged types.

Grid ring terminal mounts a cone grid support which acts as a shield between plate and filament.

A coaxial filament stem structure forms the base of the tube. This makes possible proper connections to the filament lines.

Grid and filament terminal arrangements make it possible to install or remove the 3X2500A3 without the aid of tools.

The new mechanical and electrical features of the Eimac 3X2500A3 external anode triode make it valuable for use on the VHF as well as low frequencies. More complete data and information yours for the asking.

TYPE 3X2500A3 — MEDIUM MU TRIODE

ELECTRICAL CHARACTERISTICS

Filament: Thoriated Tungsten	
Voltage	7.5 volts
Current	48 amperes
Amplification Factor (Average)	20
Direct Interelectrode Capacitances (Average)	
Grid Plate	20 $\mu\mu$fd.
Grid Filament	48 $\mu\mu$fd.
Plate Filament	1.2 $\mu\mu$fd.
Transconductance (Ib=830 ma., Eb=3000 v.)	20,000 μmhos

1123

FOLLOW THE LEADERS TO

Eimac TUBES REG. U.S. PAT. OFF.

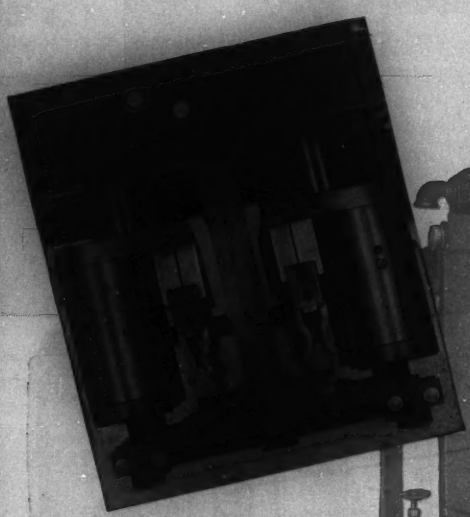
EITEL-McCULLOUGH, INC., 1123 San Mateo Ave., San Bruno, Calif.

Plants located at: San Bruno, Calif. and Salt Lake City, Utah

Export Agents: Frazar and Hansen, 301 Clay St., San Francisco 11, Calif., U.S.A.

NEW EXOTHERM

of arc extinction gives added safety

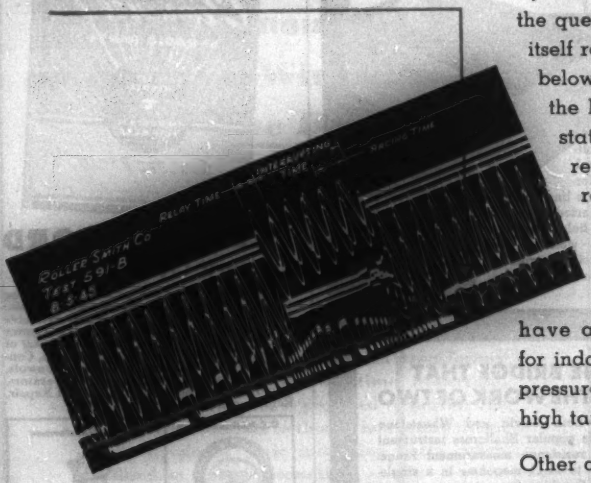


EXOTHERM ARC QUENCHERS— the reason for low tank pressures. Pressure produced by striking arc is confined.

Roller-Smith Exotherm Type Oil Circuit Breaker, 130 TCR-5; 15,000 volts; 1200 amperes; 150,000 kva.

PRINCIPLE

of Low Tank Pressures



TANK PRESSURE—Typical test oscillogram of Roller-Smith oil circuit breaker at full rated capacity—note slight fluctuation in tank pressure.

THE Roller-Smith Exotherm principle of arc extinction confines the heated gases in an arc chamber. The arc is extinguished by the combination of internal pressure and lowered gas temperature.

By harnessing the gas pressure within the quencher, the pressure in the tank itself remains at a nominal value well below any danger point. Every test at the Roller-Smith "On the Line" test station includes the tank pressure reading along with voltage, current and time. Average tank pressures do not exceed 40 pounds per square inch.

Exotherm oil circuit breakers have a far greater factor of safety for indoor use as a result of the low pressure than breakers with the usual high tank pressures.

Other advantages of the new Exotherm principle are: 5 cycle operation; reduced contact burning; reduced maintenance and inspection; more consistent arc performance.

For full information on the Exotherm principle applied to Roller-Smith oil circuit breakers, write to dept. EE-6

ROLLER SMITH

ROLLER SMITH

Oil Circuit Breakers

BETHLEHEM • PENNSYLVANIA

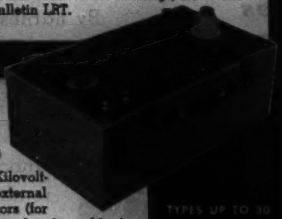
In Canada: Roller-Smith Marsland, Ltd., Kitchener, Ontario

STANDARD AND PRECISION ELECTRICAL INSTRUMENTS • AIRCRAFT INSTRUMENTS • SWITCHGEAR
AIR AND OIL CIRCUIT BREAKERS • ROTARY SWITCHES • RELAYS • PRECISION BALANCES

SHALLCROSS PORTABLE TYPE 645 FOR FIELD INSPECTION WORK

STREAMLINING LOW RESISTANCE MEASUREMENTS

Are you required to make hundreds of accurate "Go, No-Go" low resistance measurements? The Shallcross Portable Low-Resistance Test Sets are ideal for making rapid measurements in bond testing, switch and relay contact resistance testing, bar-to-bar commutator readings, etc. Write for Bulletin LRT.



TYPES UP TO 30 KV AVAILABLE FOR RAPID DELIVERY!

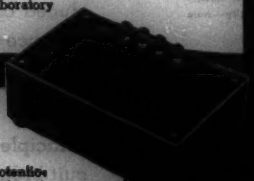
HIGH-VOLTAGE MEASUREMENT PROBLEMS SOLVED

Shallcross Portable Kilovoltmeters, Kilovoltmeter Multipliers (for use with external meters) and Corona Protected Resistors (for voltages up to 200 KV) comprise a complete line of high-voltage measuring apparatus. Over a period of years Shallcross engineers have pioneered in the field of modern high-voltage measurements. They will welcome an opportunity to put their experience to work on your problem.

TYPE 638-J COMBINED KELVIN AND WHEATSTONE BRIDGE

ONE BRIDGE THAT DOES THE WORK OF TWO

Combining both Kelvin and Wheatstone bridges, this popular Shallcross instrument provides a resistance measurement range from 0.0001 to 11.11 megohms in a single portable instrument. Just the thing for maintenance, production line tests, field investigations, school and laboratory work, etc.



TYPE NO. 845 POPULAR 3-DECADE UNIT

ACCURATE VOLTAGE DIVIDERS

Shallcross Voltage Dividers (Decade Potentiometers) are available in a wide range of total resistance and voltage increments. Many special units regularly produced for special applications. Write for latest data bulletins on any Shallcross instrument type.

Shallcross

MANUFACTURING COMPANY

DEPT. EE-125, COLLINGDALE, PA.

ENGINEERING • DESIGNING • MANUFACTURING

RADIO PARTS ELECTRONIC EQUIPMENT

FREE! CONCORD *Victory Clearance Flyer*

Ready now! 52 Bargain-packed pages listing thousands of standard-make, top-quality radio parts and electronic supplies—now available without priority at low VICTORY CLEARANCE prices. The values listed below are typical of the important savings offered in Meters, Condensers, Transformers, Resistors, Controls, Relays, Switches, Test Equipment, Generators, Microphones, Tools, and hundreds of Repair, Replacement, and Accessory Parts.

D.C. Milliammeters

2½" flange mtg. type. Metal case dull black finish. Cat. No. 0-200 M.A. Clo650. Specially priced. $4.95

Output Transformer

Hermetically sealed. Six studs 1, 2, and 3 are pri. 4, 5, 6 and 4 the sec. Pri. load at 5 V. 1000 cy.: .20 H. Ratio sec. to pri. 2.82:1. Size: 3¼ x 2 41/64" SBS645 Your cost... $1.95

Immediate Shipment from

CHICAGO or ATLANTA

these stocks in two convenient warehouses—one in CHICAGO and one in ATLANTA—are ready to supply you quickly with needed parts of dependable, extensively-known quality—and at VICTORY CLEARANCE prices that mean real savings. Mail the coupon below NOW for your FREE copy of CONCORD'S VICTORY CLEARANCE Flyer.

CONCORD

RADIO CORPORATION

Subsidiary of Radio Corporation

CHICAGO 7, ILL. ATLANTA 3, GA.

CONCORD RADIO CORPORATION
901 W. Jackson Blvd.
Dept. C-125, Chicago 7, Ill.

Please RUSH FREE copy of CONCORD'S new 52-page VICTORY CLEARANCE Flyer.

Name.....

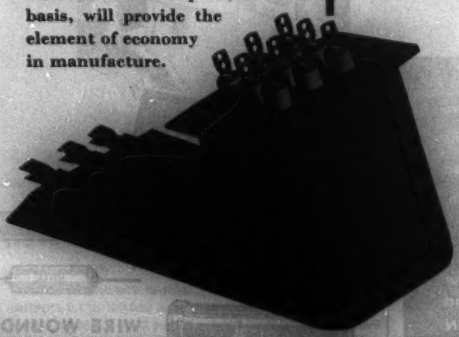
Address.....

City..... State.....

An Announcement To Those Who Require *The Best*

THIS advertisement is addressed to the manufacturers of electronic equipment whose product demands the best in component parts—who will want the best in transformers, *if* "the best" is offered at a price that will fit the cost specifications of their finished product.

By adapting to peace-time use the major features of the Hermetically-Sealed Transformer construction that won war-time leadership, Chicago Transformer is prepared to provide the best in transformers to those who require them. Fully developed basic mounting parts, when utilized on a mass production basis, will provide the element of economy in manufacture.



CHICAGO TRANSFORMER

DIVISION OF ESSEX WIRE CORPORATION

3501 WEST ADDISON STREET

CHICAGO 18

MATTHEWS HOLDFAST LAMP GUARDS

Better because they remove lamp fire hazards; they stop lamp breakage; they stop unauthorized lamp removal; they are stronger and will last longer.

They are the only lamp guards which are guaranteed for 10 years.

They are approved by Fire Underwriters.

They are made in four sizes, of 14 bwg wire and for brass or weatherproof sockets.

Write for Bulletin 401 which will give you full details including net prices.

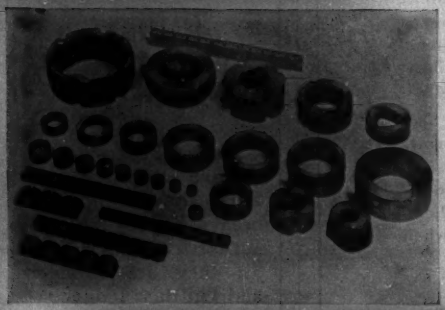
W. N. MATTHEWS CORPORATION

ST. LOUIS, U. S. A.

Permanent Magnets

FOR

LOUD SPEAKERS



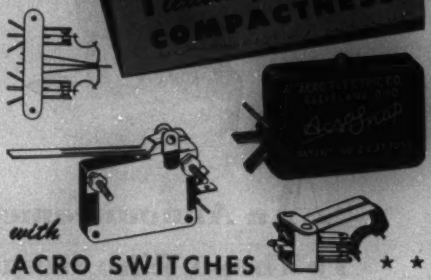
WRITE TODAY on your company letterhead FOR THIS NEW BULLETIN

THE ARNOLD ENGINEERING COMPANY

147 EAST ONTARIO STREET, CHICAGO 11, ILLINOIS

★ ★ ★

Flexibility of Design COMPACTNESS



with

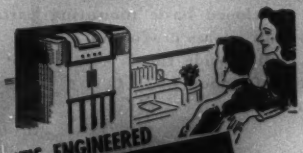
ACRO SWITCHES ★ ★

The patented ACRO rolling spring switch lends itself to the designs of your units. Multiple mountings and small case shapes—rectangular or curved—available. Operating characteristics to meet your requirements. Actuation pressure from 2 grams (using leaf bracket) to 1¼ lbs. Used widely in such applications as valve controls, coin-operated machines, microphones, electric timers, etc. If one of the many ACRO Model "M" designs does not fit your needs, surely one of the other ACRO styles can be adapted. Send design details of special limitations and operating features for quicker reply.

THE ACRO ELECTRIC COMPANY

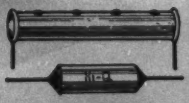
1327 SUPERIOR AVENUE • CLEVELAND 14, OHIO

DEPENDABLE PERFORMANCE



IT'S ENGINEERED WITH Hi-Q COMPONENTS

CERAMIC CAPACITORS



WIRE WOUND RESISTORS

CHOKE COILS

ELECTRICAL REACTANCE CORPORATION

FRANKLINVILLE, N. Y.

Can you use a 10,000 VOLT PLASTICON
⅛ the size of a corresponding paper capacitor?

CP

Because of the 4400 volt per mil breakdown voltage of the Plasticon film dielectric, high voltage Plasticons are smaller, lighter and more economical than paper capacitors.

*Plasticons—plastic film dielectric capacitors

Condenser Products Company
1373 NORTH BRANCH STREET
CHICAGO 22, ILLINOIS

STANDARD SIGNAL GENERATOR Model 80

SPECIFICATIONS:
CARRIER FREQUENCY RANGE: 2 to 400 megacycles.
OUTPUT: 0.1 to 100,000 microvolts. 50 ohms output impedance.
MODULATION: A M 0 to 30% at 400 or 1000 cycles internal.
Jack for external audio modulation.
Video modulation jack for connection of external pulse generator.
POWER SUPPLY: 117 volts, 50-60 cycles.
DIMENSIONS: Width 19", Height 10¼", Depth 9½".
WEIGHT: Approximately 35 lbs. PRICE—$465.00 f.o.b. Boonton.
Suitable connection cables and matching pads can be supplied on order.

MEASUREMENTS CORPORATION
BOONTON NEW JERSEY

TRANSFORMERS FOR POSTWAR ELECTRONIC APPLICATIONS

● Designed to meet your specifications, mechanically and electronically.

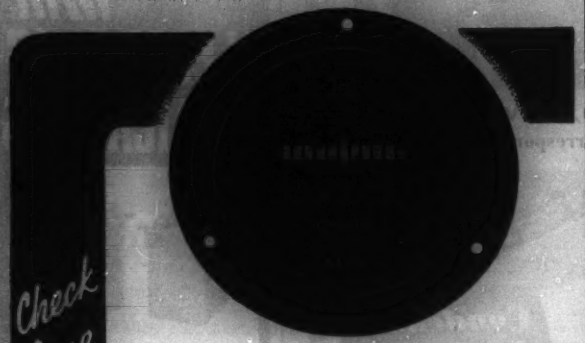
Open type, plastic impregnated transformers provide adequate weatherproofing for certain applications.

This special Radio Power transformer consists of primary winding, high voltage secondary winding and filament winding.

THE ACME ELECTRIC & MFG. CO.
CUBA, N.Y.

Acme Electric
TRANSFORMERS

How to Get Your Money's Worth in FREQUENCY METERS



Check These Points

Model 33-F, Full-cycle increment, shown indicating frequency of 60 cycles. Black dial for special application.

Here are the facts on J-B-T VIBRATING REED FREQUENCY METERS

ACCURACY — Half-cycle increment, ±0.2%; full-cycle increment, ±0.3%. This accuracy is not affected by normal temperature change, wave form or external magnetic fields.

COMPACTNESS — Made in several sizes, most popular of which is the standard 3¼" panel mounting model. Also made to meet C39.2-1944 ASA specifications and Jan-I-6 for mounting and stud size of Electrical Indicating Instruments. No external reactor.

WEIGHT — Model 31-F, 3½ inch, 5 reeds, weighs only 0.54 lb; Model 33-F, 3½ inch, 11 reeds, 0.59 lb. Other models are correspondingly *light*.

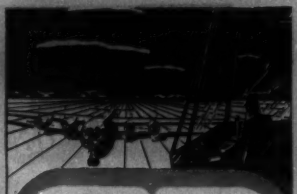
VOLTAGE VARIATION — Will operate on voltages as low as 8 volts. Standard 110-115 volt models will operate satisfactorily over range of 100 to 130 volts. Also made for narrower voltage variation if desired. (Incidentally, current consumption is low. For Model 33-F, for example, ½ watt at 115V.)

RUGGEDNESS — No parts to wear out or get out of calibration. All are securely anchored to the base with lock washers at every critical point. The only movement is at the free end of the spring steel reed. J-B-T meters on portable field equipment have established an enviable performance record.

J-B-T Vibrating Reed Frequency Meters are available for frequencies from 12 cycles to 525 cycles with various reed groupings, increments and case sizes. For additional facts on the complete line, send for Bulletins VF-43, VF-43-1A (400 cycle Meters) VF-43-1B (2½" sizes), and VF-43-1C (interesting new applications).

J-B-T

(Manufactured under Triplett Patents and/or Patents Pending)



An invitation to all electrical designers to

TRY SILVER GRAPHALLOY

FOR RELAYS • MOTORS • CONTROLS • ELECTRONICS

GRAPHALLOY

FOR BRUSHES

High current density, low contact drop, low electrical noise, and self-lubrication are characteristics of this silver-impregnated molded graphite that may be the answer to your electrical brush problems.

FOR CONTACTS

Low contact resistance and non-welding when breaking surge currents are inherent properties of this unique combination of conductive silver and self-lubricating graphite.

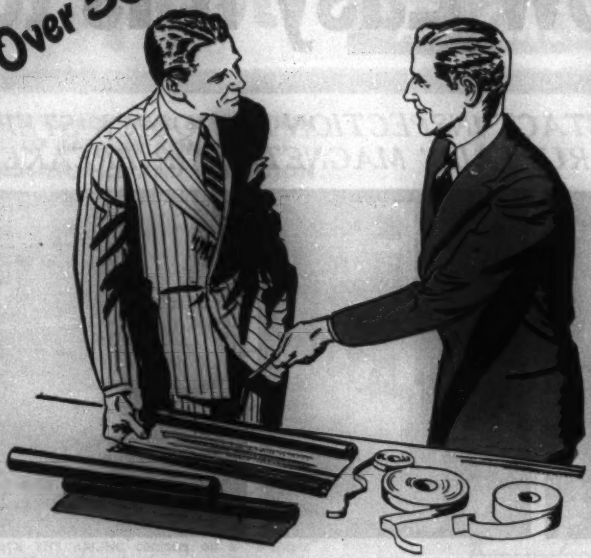
SLIP-RING AND COMMUTATOR

BRUSHES AND CONTACTS

GRAPHALLOY

GRAPHITE METALLIZING CORPORATION

Over 300% increase in 3 years



. . . THE SWING IS TO VARNISHED FIBERGLAS* CLOTH FOR ELECTRICAL INSULATION

It's because of the unique combination of characteristics, found only in Fiberglas, so many electrical engineers have standardized on Fiberglas-base Electrical Insulation Materials.

THICKNESSES OF FIBERGLAS CLOTH

Fiberglas Cloths for varnishing are produced in thicknesses from .0015" to .015" permitting a wide variety of base cloths for various varnished thicknesses. Thickness of base cloth and finished thickness of varnished cloth should be determined by space-factor, dielectric strength and mechanical requirements of the particular application.

VARNISHED CLOTH AND TAPE

When properly impregnated, Fiberglas-base Insulation material has exceptional dielectric strength and insulation resistance. In addition it has unusually good moisture and temperature resistance and high tensile strength. The strength-to-thinness ratio of varnished Fiberglas Cloth is unmatched.

Varnished Fiberglas Cloth, in thicknesses from .003" to .030", is used wherever a high-dielectric material with good mechanical characteristics is required for equipment operating in high temperature, under adverse operating conditions, or where a greater factor of safety is desired. Typical applications are: phase insulation in a-c motors; high-dielectric and high-temperature coil insulation; ground insulation on the slot sections of preformed coils; layer insulation in air-cooled transformers, etc.

PERMITS USE OF THINNER INSULATION

Because of its higher dielectric strength and because it retains its mechanical and electrical characteristics under prolonged exposure to adverse conditions, thinner varnished Fiberglas Cloth or Tape than that required by the use of other materials will give equal or greater insulation.

Varying degrees of flexibility in varnished Fiberglas Cloth, of the same finished thickness and type of varnish, are possible by varying the thickness of the Fiberglas Cloth used as the base —yellow or black varnish treatment.

COMPLETE INFORMATION

If you do not have complete information on all types of Fiberglas-base Electrical Insulation Materials, write for Catalog EL 44-7 today. *Owens-Corning Fiberglas Corporation, 1859 Nicholas Building, Toledo 1, Ohio.*

In Canada, Fiberglas Canada Ltd., Oshawa, Ontario.

There is a **FIBERGLAS** Insulation Material for every need

Untreated, continuous filament, Fiberglas Cloth is made in thicknesses from .0015" to .015" — staple fiber cloth from .012" to .023".

Varnished Fiberglas Cloth is available in 36" widths or cut to any desired tape width.

Treated and untreated Fiberglas Tapes in various widths and thicknesses are used in winding all types of coils.

Write for Catalog E 44-7

FIBERGLAS

*T. M. Reg. U. S. Pat. Off.

ELECTRICAL INSULATION MATERIALS

Each distributor of Fiberglas-base Insulation Materials has his own source of supply, since Owens-Corning Fiberglas Corp. does not process these materials.

See How Easy it Is to

ROUTINE CONTACT INSPECTION IN 3 QUICK STEPS ON OILLESS "RUPTAIR" MAGNETIC AIR BREAKER

1 LOWER BREAKER. Photo shows "Ruptair" magnetic air breaker in operating position (at right) and in the lowered disconnect position. The breaker is easily lowered with manually or electrically operated crank-hoist.

2 WITHDRAW BREAKER. In disconnect position, the "Ruptair" breaker can be placed on a transfer truck, and pulled out into the aisle. For safety, shutters to isolate disconnect contacts are automatic in operation.

3 REMOVE SIDE PLATES. Finally, light-weight insulating barriers are removed, each barrier being held in place by two cap-screws. Since the arc chute is above the contacts, it need not be disturbed for contact inspection.

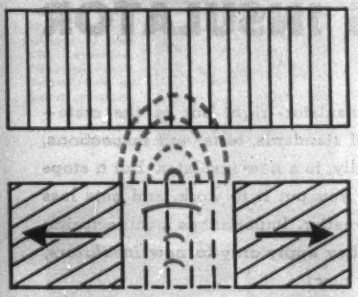
AS A MODERATE capacity, oilless circuit interrupter, the "Ruptair" breaker is gaining increased popularity among operators. Elimination of oil means many more repetitive operations without maintenance . . . reduced fire hazard . . . less danger from breaker failure.

In addition to these advantages, and simplest inspection of any magnetic air breaker, the "Ruptair" breaker combines space saving vertical lift construction with horizontal contact separation, shown at top of opposite page. "Ruptair" circuit breakers are built in standard ratings of 5 kv and below, 150,000 kva interrupting capacity and below, for installation in metalclad switchgear, cells, or cubicles. To get the full story, write Allis-Chalmers, Milwaukee 1, Wis.

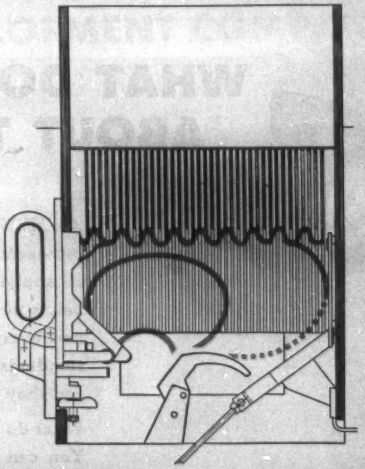
Inspect

A "RUPTAIR" MAGNETIC AIR CIRCUIT BREAKER

WITH HORIZONTAL SEPARATION OF BREAKER CONTACTS, MAINTENANCE AND OPERATION ARE SIMPLIFIED



SINCE THE ARCING contacts on a "Ruptair" magnetic air circuit breaker are separated in the horizontal direction, natural thermal effect assists the arc into the arc chute . . . no complex interrupting structure is required! Position of arc chute *above* contacts makes it possible to inspect contacts without removing the chute. Maximum interrupting effectiveness is achieved in the "Ruptair" circuit breaker, without departing from ideal simplicity of design.



RUPTAIR BREAKER HAS UNIQUE DESIGN

THE RUPTAIR breaker depends for its high efficiency throughout interrupting current range on several design factors . . . coordination of horn-shaped moving contact and arc runner for quick transferral of the arc . . . establishment of a strong magnetic field in the breaker before actual contact separation . . . and special design of the arc chute.

Why Allis-Chalmers offers all 3 types of Circuit Breakers

☛Ever hear of "special theater modifications"? That's a military term, and refers to the adaptation of aircraft to unusual flying conditions, such as are encountered in Central Alaska, or in torrid tropical climates.

☛An airplane built for special theater operations often differs in practically every detail from a plane designed for duty under normal atmospheric conditions. That is, the Army and Navy have learned that *one* type of plane can't function in *all* theaters of war!

☛*For the same reasons, Allis-Chalmers engineers know that one type of circuit breaker won't do the job in all the varied environments encountered in industry.*

☛Therefore, it is an Allis-Chalmers switchgear policy to offer *all three* basic types of circuit interruptors — oil, magnetic air, and air blast breakers — for unrestricted customer choice. Neither by price penalties, or any other means, does Allis-Chalmers seek to coerce buyers into selecting any *one* type of breaker.

☛Thus the customer has a means of expressing his circuit breaker preference, based on intimate knowledge of local operating conditions. And indirectly, through the medium of free choice, he influences the future trend of switchgear development. A 1863

A-C ALLIS-CHALMERS
MILWAUKEE

WHAT DO YOU KNOW ABOUT THIS INSULATOR

A NEW station insulator--right out of the crate--represents a host of standards, tests, and inspections, all applying, naturally, to a *new* insulator. But it stops being new the day you put it to work, and gets less new every year thereafter. Important as manufacturing standards may be, they apply only to *new insulators*, and they don't *stay* new!

What do you know about *old* O-B station insulators? You can go back some 30 years of continuous performance, or pick almost any quantity. You can inspect authentic power company records that produce incontestable facts. You will see why most O-B station insulators, today, are bought on repeat orders based upon previous service.

In a new station insulator, you can't reliably predict long future life. Time, alone, furnishes this answer. It is found in long service records--the kind of records O-B has been piling up for better than a quarter of a century. The one thing you want the most--reliability--can't be specified or predicted in tests. It is an inherent quality put there by the man who makes the insulator. Just how much O-B has put into its insulators is a matter of adequate record.

2612-H

Ohio Brass

MANSFIELD, OHIO

CANADIAN OHIO BRASS COMPANY, LIMITED
NIAGARA FALLS, ONTARIO

TRANSTATS
maintain voltages to a hairline at GULF RESEARCH & DEVELOPMENT COMPANY

Pilot Plant Control Panels, Gulf Research & Development Company, division of Gulf Oil Corporation, Pittsburgh, Penna. Transtat knobs are below ammeters.

TH TRANSTAT
A. C. VOLTAGE
REGULATORS
For 0.3 to 20 KVA

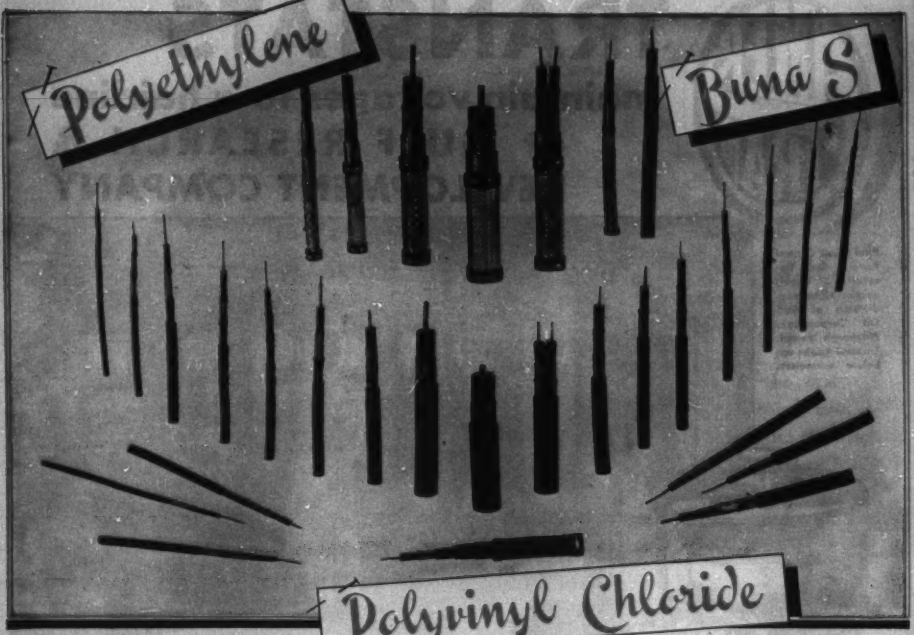
In Gulf's Research Laboratories, unusual precautions are taken to eliminate variations. For example, fifty-six Transtat A. C. Voltage Regulators maintain required voltages to the heating elements inserted between pipe and insulation to compensate for heat lost. The extreme precision and ruggedness of Transtats results from the unique side-commutation. The long, cooler running brush rides on a glass-smooth track, providing arcless, stepless control. Bulletin 51-2 gives construction details. Write for it.

Showing Transtats mounted on rear of panel.

AMERTRAN

AMERICAN TRANSFORMER COMPANY
178 EMMET STREET, NEWARK 5, N. J.

Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission



These are the insulations used on the Coaxial cables we have made during the war. The cable characteristics vary widely both electrically and physically but their quality is uniformly high.

If you have Coaxial cable requirements perhaps one of these will do what you require. If not, we will be more than happy to design a special cable to meet the specific requirements you have in mind.

REMEMBER THAT THE LATEST ADVANCES IN CABLE DESIGN AND MATERIALS COME FROM SIMPLEX FIRST.

Simplex Wire & Cable Co., 79 Sidney Street, Cambridge 39, Mass.

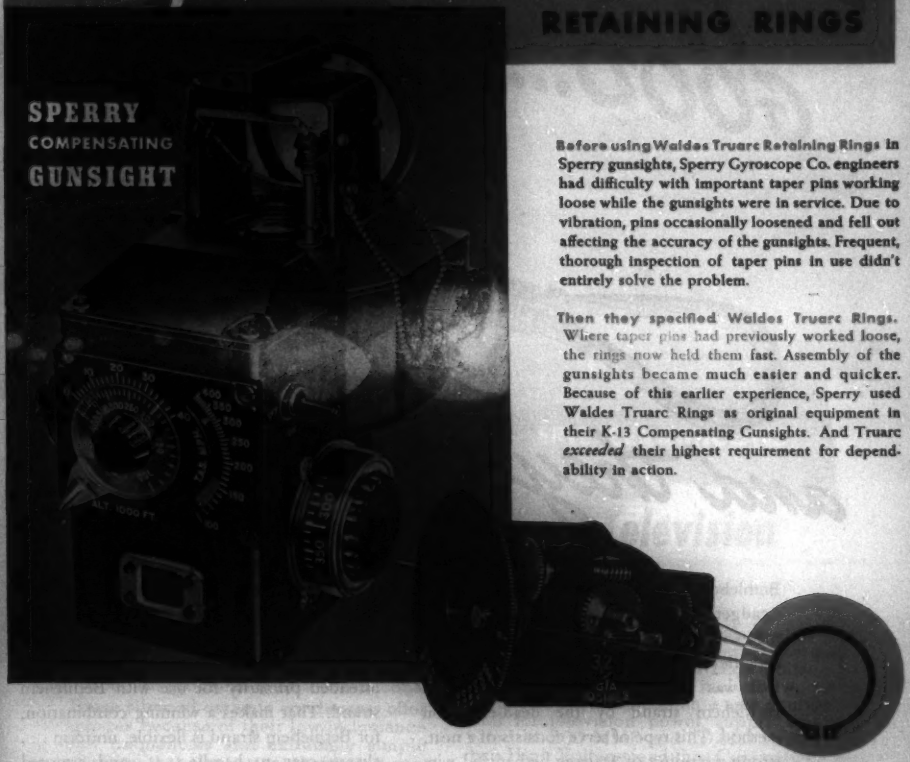
ARMY E NAVY M

Simplex WIRES and CABLES

Sperry FOUND A BETTER WAY

TO HOLD MACHINE PARTS TOGETHER

WALDES TRUARC RETAINING RINGS

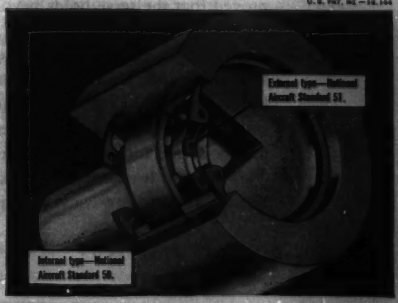


Before using Waldes Truarc Retaining Rings in Sperry gunsights, Sperry Gyroscope Co. engineers had difficulty with important taper pins working loose while the gunsights were in service. Due to vibration, pins occasionally loosened and fell out affecting the accuracy of the gunsights. Frequent, thorough inspection of taper pins in use didn't entirely solve the problem.

Then they specified Waldes Truarc Rings. Where taper pins had previously worked loose, the rings now held them fast. Assembly of the gunsights became much easier and quicker. Because of this earlier experience, Sperry used Waldes Truarc Rings as original equipment in their K-13 Compensating Gunsights. And Truarc *exceeded* their highest requirement for dependability in action.

Waldes Truarc Retaining Rings are used to save weight, space, cost and man-hours in a wide range of products. For holding and positioning machine parts they offer definite advantages over nuts, shoulders, collars, and pins. They simplify and speed up production. They can be put on and taken off again and again —and still retain the perfect circularity which gives them their unfailing grip. Test them yourself. We'll furnish samples and complete data. Write Dept. F-12.

U. S. PAT. NO. —18,144



WALDES TRUARC Trade Mark **RETAINING RINGS**

WALDES KOHINOOR, INC., LONG ISLAND CITY 1, NEW YORK

CANADIAN REPRESENTATIVES: PRENDO PRODUCTS CORP., LTD., 72-74 STAFFORD ST., TORONTO

Linemen Say IT'S GOOD...

and they should know

Bethlehem's serving tool has the look of a "gadget" and a funny one at that. Yet linemen will tell you that it's one of the handiest little devices that ever came along.

It was designed for making serves on Bethlehem strand by the dead-end coil method. This type of serve consists of a neat, strong wrapping of 11-gage bethanized wire around the dead end. Extensive tests have proved that the serve holds beyond the useful strength of the strand.

Even a novice can learn the technique in a few minutes' time. The lineman simply hooks one end of the wire to the strand, as shown, and engages it between the two fingers of the tool. A simple rotary motion does the rest. It takes about the same length of time as attaching conventional clips, but is less expensive. A 10-foot coil of bethanized dead-end wire costs only a few pennies.

We strongly recommend that you equip your linemen with these tools, which are intended primarily for use with Bethlehem strand. That makes a winning combination, for Bethlehem strand is flexible, uniform . . . always easy to handle . . . and armored against corrosion by a bethanized zinc coating of high purity. This coating is so ductile that it is not displaced to any harmful extent by the action of the serving tool.

Write Bethlehem Steel Co., Bethlehem, Pa., for further details. We'll gladly supply them.

★ BETHLEHEM STEEL ★

For Electr... ...d Television Capaci... ...plications

WITH the growing importance of electronic heating and television, design engineers can find the solution to many of their capacitor problems in Erie Ceramicons.

These silvered-ceramic condensers offer advantages because of their low inductance at high frequencies and extremely simple construction that eliminates circulating currents tending to reduce power ratings. Design is further simplified by the fact that where required, corona shields are incorporated directly into the ceramic dielectrics.

Erie Resistor has developed a number of High Voltage and High KVA Ceramicons of special design and several standard styles are now in production. Included in the above group is a specially designed 30,000 volt feed-thru Ceramicon; a dual filament by-pass unit having conductors to carry 325 amps. The standard Erie Resistor High Voltage ceramic condensers shown include two styles of double cup Ceramicons; a new double cup unit for television power supply filtering, rated at 500 MMF and 10,000 volts D. C.; two High Voltage feed-thru Ceramicons; and a High KVA, High Voltage, multiple plate condenser comparable in size to mica type CM75 but particularly adapted to use at very high frequencies.

Write for data sheets on standard Erie Ceramicons for television and electronic heating applications. You are invited to make use of our extensive knowledge and background for the development of special Ceramicons for these applications.

*CERAMICON IS THE REGISTERED TRADE NAME OF SILVERED CERAMIC CONDENSERS MADE BY ERIE RESISTOR CORPORATION.

★ BUY VICTORY BONDS ★

Electronics Division

ERIE RESISTOR CORP., ERIE, PA.

LONDON, ENGLAND TORONTO, CANADA.

USE THIS COMPLETE BRUSH-TESTING LAB!

FOR FRACTIONAL HORSEPOWER MOTOR BRUSHES

HERE'S a modern laboratory for testing fractional horsepower motor brushes. It's air conditioned . . . equipped with the latest test facilities . . . staffed by experts . . . backed by over half a century's experience in brush manufacturing.

IT'S AT YOUR SERVICE! WE URGE YOU TO MAKE USE OF IT!

This lab relieves you of making countless time-consuming and costly "elimination tests." Here your motors are tested as you would test them yourself . . . under your own specified load, cycle, and test conditions.

From such tests National Carbon Company, Inc. establishes the proper brush grade for any particular model or type of motor, be it Series Universal, Repulsion-Induction, or for low voltage service. And because these tests are most thoroughly conducted you can be sure that the most suitable grade has been applied.

No delays—tests are made promptly! So send in your motors—make use of this lab!

For more details get in touch with our nearest division office.

A FEW OF THE TESTS RUN

Tests are run to determine optimum performance in respect to:

commutation • commutator condition
quietness of operation
brush life • operating temperature

The word "National" is a registered trade-mark of National Carbon Company, Inc.

NATIONAL CARBON COMPANY, INC.

Unit of Union Carbide and Carbon Corporation

UCC

General Offices: 30 East 42nd Street, New York 17, N. Y.

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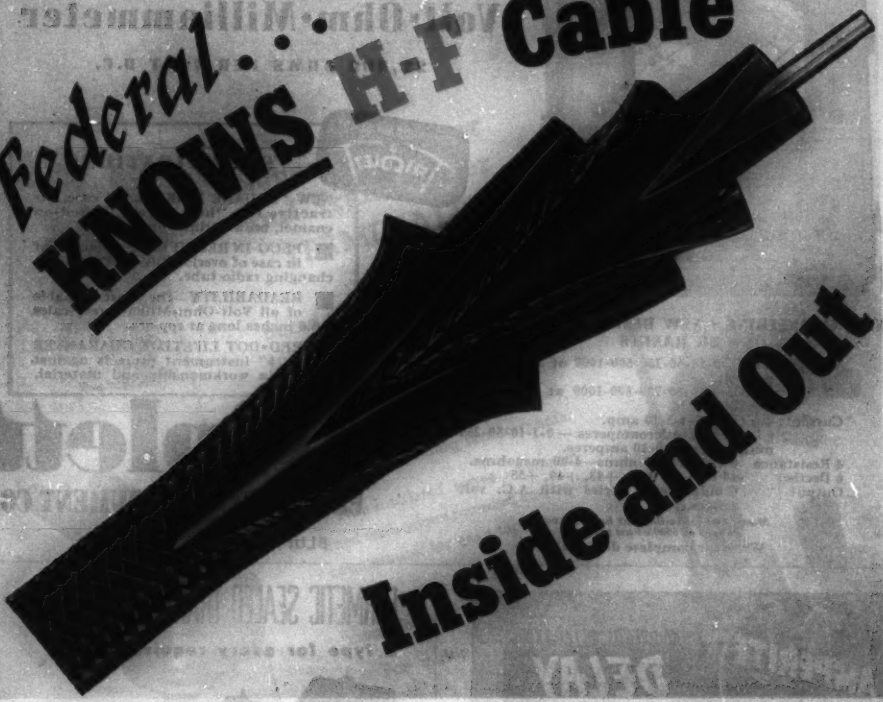
Federal . . . KNOWS H-F Cable Inside and Out



From inner conductor to outer covering . . . Federal really knows high-frequency transmission lines.

And this knowledge was not easily won. As the pioneer in the field Federal not only developed over 80% of all h-f cable types in use today . . . but developed most of the equipment needed to test them.

Attenuation, high-voltage, dielectric and balance testing equipment, velocity of propagation, braid-resistance and electrical length meters . . . were all Federal-*engineered* to fit specific requirements.

That's why it's logical to turn to the acknowledged leader in the field for the finest in h-f cables, specialty-engineered harnesses and cable assemblies.

Where requirements are critical . . . for transmission lines with special characteristics . . . for custom-built and engineered harnesses and cable assemblies . . . take your high-frequency transmission problems to Federal.

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MODEL 2405

Volt·Ohm·Milliammeter

25,000 OHMS PER VOLT D.C.

NEW ENGINEERING • NEW DESIGN • NEW RANGES
30 RANGES

Voltage: 5 D.C. 0-10-50-250-500-1000 at 25000 ohms per volt.
5 A.C. 0-10-50-250-500-1000 at 1000 ohms per volt.
Current: 4 A.C. 0-.5-1-5-10 amp.
6 D.C. 0-50 microamperes — 0-1-10-50-250 milliamperes—0-10 amperes.
4 Resistance 0-4000-40,000 ohms—4-40 megohms.
6 Decibel -10 to +15, +29, +43, +49, +55
Output Condenser in series with A.C. volt ranges.

Model 2400 is similar but has D.C. volts Ranges at 5000 ohms per volt.

Write for complete description

SPECIFICATIONS

NEW "SQUARE LINE" metal case, attractive tan "hammered" baked-on enamel, brown trim.

- PLUG-IN RECTIFIER—replacement in case of overloading is as simple as changing radio tube.
- READABILITY—the most readable of all Volt-Ohm-Milliameter scales —5.6 inches long at top arc.
- RED•DOT LIFETIME GUARANTEE on 6" instrument protects against defects in workmanship and material.

Triplett
ELECTRICAL INSTRUMENT CO.
BLUFFTON OHIO.

AMPERITE

THERMISTANIC METAL TYPE

DELAY RELAYS

PROVIDE DELAYS RANGING FROM 1 TO 120 SECONDS

Other important features include:

1. Compensated for ambient temperature changes from —40° to 110°F.
2. Contact ratings up to 115V-10a AC.
3. Hermetically sealed — not affected by altitude, moisture or other climate changes . . . Explosion-proof.
4. Octal radio base permits easy replacement.
5. Compact, light, rugged, inexpensive.
6. Circuits available: SPST Normally Open; SPST Normally Closed.

WHAT'S YOUR PROBLEM? Send for "Special Problem Sheet" and Descriptive Bulletin.

with porcelain heater

with heater wound directly on sleeve

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HERMETIC SEALED TRANSFORMERS

a type for every requirement

May we cooperate with you on design savings for your application....war or post war

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Burndy makes many types, including—
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All are fully described in catalog #8001. Send for your copy. Burndy Engineering Co., Inc., 107-E Bruckner Blvd. New York 54, N. Y.
Manufacturers for CONNECTIONS
Burndy

SELF CONTAINED 2300 VOLT OIL IMMERSED A.C. INDUCTION MOTOR CONTROL

CONSTRUCTION AND OPERATING FEATURES

1. They have an especially designed, quick-acting, heavy-duty contactor.
2. High interrupting disconnect fuses, hook stick operated.
3. Self-contained, seal-off motor terminal compartment.
4. Centralized self-contained low voltage control terminal compartment.
5. Magnetic overload relays with electric reset, instantaneous and inverse time element.
6. Self-contained control potential transformer.
7. Self-contained Tank lowering device.
8. Insulated Bus, supported on porcelain insulators.

The simplicity, efficiency, and flexibility of this Push Button operated Control have been made possible by Rowan Engineers after thirteen years of research, and production of this type of equipment. It has been designed for Engineers whose prime thoughts are safety, continuous operation, minimum installation and maintenance cost. These starters are floor mounted and are arranged for single or group installation. They are Push Button operated; of the full voltage or reduced voltage type; arranged for indoor, or outdoor service; are of cubicle construction and are complete within themselves. *Let us have your 2300 Volt control problems.*

ROWAN CONTROL

THE ROWAN CONTROLLER CO., BALTIMORE, MD.

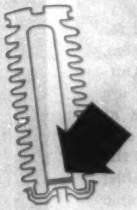
LINE POST LINES HAVE FEWER INSULATOR OUTAGES FROM FLASHOVER

The Line Post design offers an insulator peculiarly adapted to withstand the shattering forces of power arcover. A rugged post body, it attains leakage distance through the device of many short sturdy petticoats rather than few thin, broad, spreading sections. Repeated flashover usually leaves a unit undamaged. If, under severe flash, a unit is fractured, flashover and leakage distances are not reduced enough to impair the serviceability of the insulator.

LAPP LINE POSTS HAVE A DOUBLE FACTOR OF SAFETY...

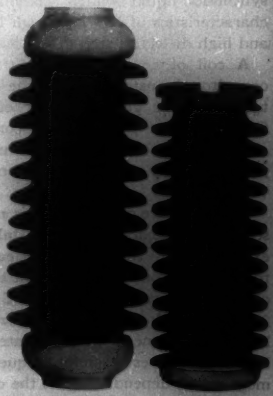
1 POSITIVE SEAL

The 15-year service record of Lapp Line Posts is witness to the soundness of Lapp techniques of Post construction. One exclusive Lapp feature is a combination porcelain-and-rubber plug which permanently seals the lower end of the post against moisture.



2 NO HIDDEN CRACKS

Failure of any post-type insulator can usually be attributed to unnoticed internal cracks near the head of the insulator. All Lapp posts are fired with the lower end open, permitting critical inspection of finished porcelain before assembly.



Lapp

LAPP INSULATOR COMPANY, INC., LE ROY, N. Y.

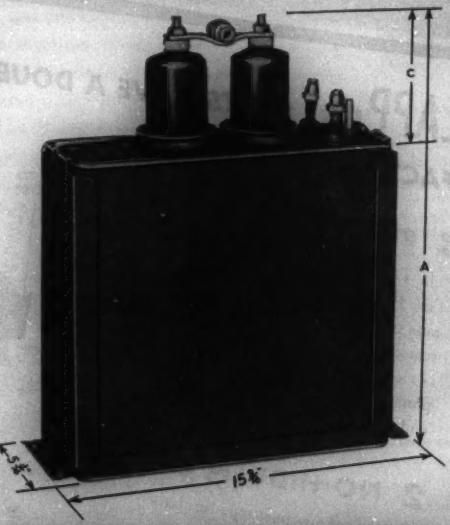
HERE 3 CAPACITORS DO TWICE THE WORK OF 25

A MANUFACTURER of induction heaters replaced 25 mica capacitors in his resonant (tank) circuit with three General Electric HFP parallel-plate, water-cooled capacitors. He saved nearly half the cost and space, and more than doubled the kva. Result: a more compact, more powerful, and more efficient heater.

Class HFP capacitors, with their two sets of heavy, sheet-aluminum plates, are specifically designed for use in resonant circuits of high-frequency oscillators, such as those employed in electronic heaters. Outstanding features of Class HFP capacitors are compact construction, and ability to operate at high voltages and to carry heavy continuous currents at frequencies from 50 kilocycles up into the megacycles. The special dielectric is a new, stable, synthetic liquid which combines the desirable characteristics of low loss, high dielectric constant, and high dielectric strength.

A coil of copper tubing, for water-cooling the capacitor, is installed inside the case in direct contact with the grounded pair of capacitor plates. Couplings are provided for connection to 3/8-in. copper tubing. The cooling feature permits a compact assembly and high current rating per unit volume.

The cases are of nonmagnetic metal, hermetically sealed, and flexible enough to take care of thermal expansion of the liquid dielectric. Capacitance tolerance is from plus 5 per cent to minus 5 per cent of the rated capacitance at 25 C; Q factor is above 2000 for full load operation at frequencies from 50 kilocycles to one megacycle. Internal inductance is low, which gives resonant frequencies from 3 to 9 megacycles, depending upon the capacitance rating. Write for Bulletin GEA-4365. *Apparatus Dept., General Electric Company, Schenectady 5, N. Y.*



Maximum Permissible Rms Working Voltage	Microfarad Rating	Maximum Permissible Rms Working Current in Amp at 540 Kilocycles	Approximate Dimensions in Inches	
			A	C
2000	0.025	170	16 7/32	2 1/2
	0.030	204		
	0.034	230		
3000	0.0165	168	16 7/32	2 1/2
4000	0.0075	153	18 7/16	4 7/16
	0.01	204		
6400	0.009	202	18 7/16	4 7/16
	0.0029	88		
9600	0.005	153	18 7/16	4 7/16
	0.0056	171		

Keep on buying BONDS—and keep all you buy

DIGEST

Timely Highlights on G-E Components

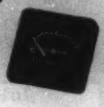
LIGHT-WEIGHT TRANSFORMERS

for tight spots

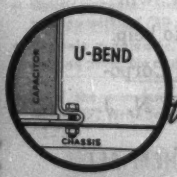
When size and weight are important and weather resistance isn't, G-E core-and-coil transformers solve a lot of electronic-design problems. Uniform coils, automatically wound over the finest-grade core laminations, are of the same high quality and give the same reliable performance as G-E cased transformers.

Standard core and coil units include 60 types and ratings of plate transformers, 106 filament transformers, 34 plate-and-filament transformers, and 61 reactors. Ratings up to 50 kva (physical size) are wound on standard laminated cores; larger units can be built from special parts. Write for Bulletin GEA-4280.

Small ONLY IN *Size*



Inside these G-E small panel instruments are packed accuracy and reliability usually associated with larger G-E instruments. They have space-saving internal-pivot construction. They respond quickly. Accurate readings are easily made. The instrument weighs a mere 3 ounces and is just 1½ inches wide and less than 1 inch deep. Either watertight or conventional construction is available for direct-current, audio-frequency and radio frequency applications. Write for Bulletin GEA-4380.



BRACKETS

that hold their own

A distinct advance in bracket design simplifies the mounting of rectangular-cased G-E capacitors. A U-bend replaces the conventional L-shape and provides a spring-washer effect for secure capacitor mounting. At the same time, it reduces strain on both capacitor and chassis, and compensates for tolerances in capacitor case heights.

For either base or inverted mounting, U-bend brackets are available for most G-E rectangular-case a-c and d-c capacitors. Write for Bulletin GEA-4357.

Capacitors • Sensitive control and time-delay relays • Limit switches • Motors, dynamotors, amplidynes • Motor-generator sets • Alnico magnets • Small panel instruments • Formex* magnet wire • Radio transformers • Switchettes • Selsyns • Chokes • also tubes, crystals, plastics products, insulation materials, and many others

General Electric Company
Apparatus Dept., Sec. 642-10
Schenectady 5, N. Y.

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☐ GEA-4365 ☐ GEA-4280
☐ GEA-4380 ☐ GEA-4357

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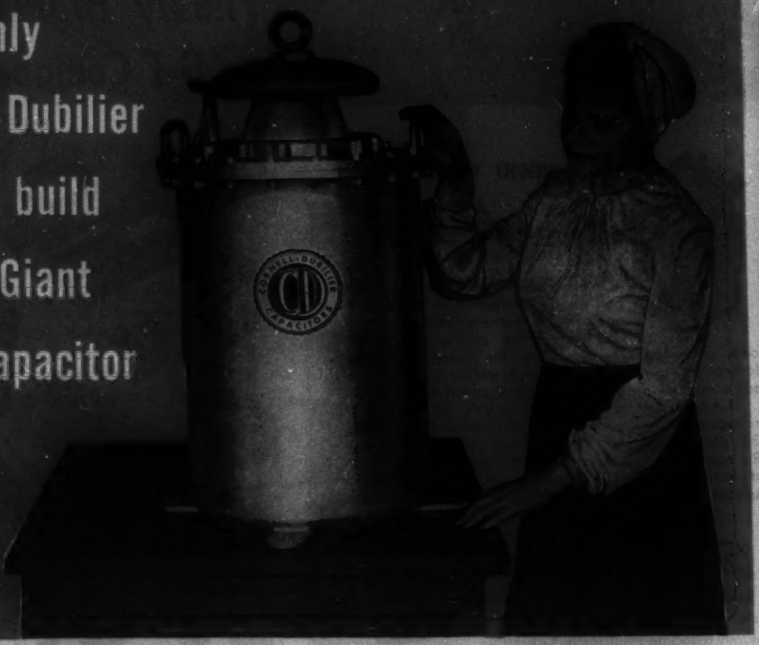

When an unusual problem in capacitors arises, engineers think first of C-D. A case in point is this giant mica tank capacitor for a transoceanic transmitter. It is now in use and combines space-saving design with the capacity of much larger units.

No matter what kind of capacitor you require, C-D can design and build it for you. Discuss your capacitor requirements with our engineers. They will welcome the opportunity to help. Cornell-Dubilier Electric Corporation, South Plainfield, N. J.

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First in Quality **CAPACITORS**

Boost the Performance

OF YOUR EQUIPMENT

with

RAYTHEON VOLTAGE STABILIZERS

THE PRECISION, accuracy and dependability of much electrical equipment are impaired by varying supply voltages.

If varying power supply handicaps your equipment why not install magnetic-type RAYTHEON VOLTAGE STABILIZERS? Long-proved, job-rated, and designed to meet practically any installation need, they are *boosting performance* in a wide variety of electrical equipment in many useful applications.

Get these principal operating advantages:

- **Control of output voltage to within ±½% of 115 or 230 V.**
- **Stabilization at any load within rated capacities.**
- **Quick response. Stabilizes varying input voltage within 1/20 second.**
- **Entirely automatic. No adjustments. No moving parts. No maintenance.**

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For Radio • Television • Communications Radar • Motion Pictures Sound Recording Electronic Devices • Constant Speed Motors Production Machinery • Signal Systems X-ray Equipment • Testing and Laboratory Equipment.

RAYTHEON
MANUFACTURING COMPANY
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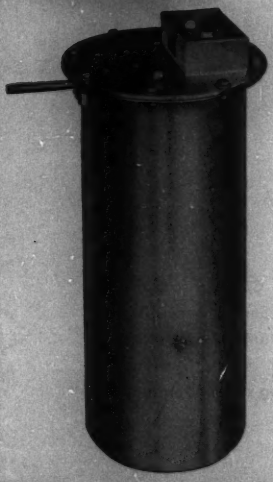
ELECTRICAL EQUIPMENT DIVISION
Excellence in Electronics

Oil cooled POWERSTATS

Increased Rating

The "factory built" Oil-Cooled POWERSTAT Variable Transformers pioneered by SUPERIOR ELECTRIC COMPANY fulfill the demand for a variable transformer having the following features . . .



- HIGH CONTINUOUS RATING: Oil-Cooled POWERSTAT Variable Transformers are designed to operate continuously at currents which are double the air-cooled current rating.
- HIGH MOMENTARY OVERLOAD CAPACITY: Cooling oil in all parts of the POWERSTAT permits high current overloads of short duration to be applied to the unit.
- INCREASED VOLTAGE TO GROUND: POWERSTATS can be safely used at higher potentials to ground because of the high dielectric strength of transformer oil.
- SAFETY IN HAZARDOUS LOCATIONS: All connections are submerged under oil so the Oil-Cooled POWERSTATS may be safely used in explosive atmospheres.
- SCIENTIFICALLY DESIGNED CONTAINERS: The Oil-Cooled POWERSTATS are scientifically designed with optimum radiating area, adequate oil circulation and high conductivity tanks.

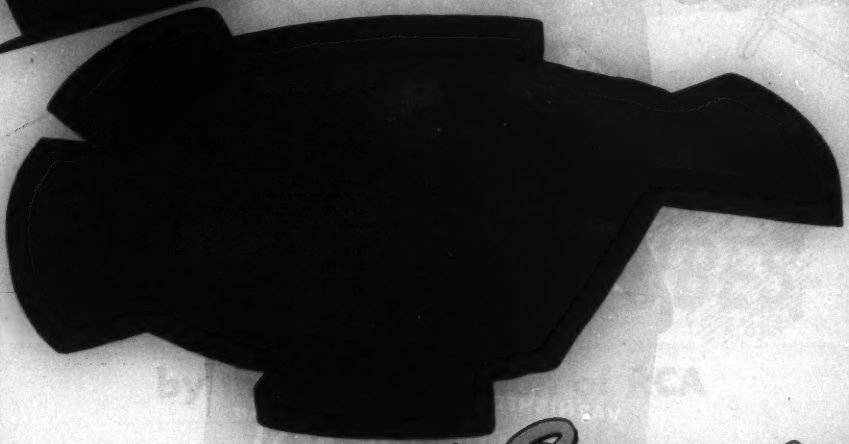
Send for Bulletin EE

SUPERIOR ELECTRIC COMPANY

509 LAUREL STREET • BRISTOL, CONNECTICUT

"LET'S TAKE IT APART"

IT'S EASIER SAID THAN DONE



. . . it's Copperweld!

We really punished this sample—cut from a Copperweld ingot—to test the molten-weld between the copper and the alloy steel core.

Saw cuts were made radially at several points completely through the copper and into the alloy steel. The segments were bent backwards and forwards until fracture resulted. The copper broke under repeated bending but not once did the break occur in the area of the molten-weld.

While Copperweld is continually improving its products, the original and exclusive Copperweld principle of the molten-weld is so sound that it has never had to be changed.

Thirty years of successful performance in the power, communication and railroad industries attests the fact that you can always depend on Copperweld wherever you need a high quality wire with the strength of steel and the conductivity and long life of copper. Engineering data on request.

In all the world there is only one COPPERWELD—with copper molten-welded to alloy steel.

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Dieflex Varnished Tubing Products are made of closely braided sleevings completely impregnated and treated with special insulating varnishes. A smooth inside bore to prevent snagging, uniformity of size, complete roundness, maximum flexibility, and excellent ageing qualities are found in all Dieflex products. They do not fray or pinch when cut.

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Dieflex Varnished Tubing Products—both cotton and Fiberglas base—are made to meet and surpass the V.T.A. and A.S.T.M. standards. Grade A-1 Magneto quality, Grade B-1 Radio quality varnished tubings, and Grades C-1 Extra Heavily Coated, C-2 Heavily Coated, and C-3 Lightly Coated Saturated Sleevings are "tops in quality."

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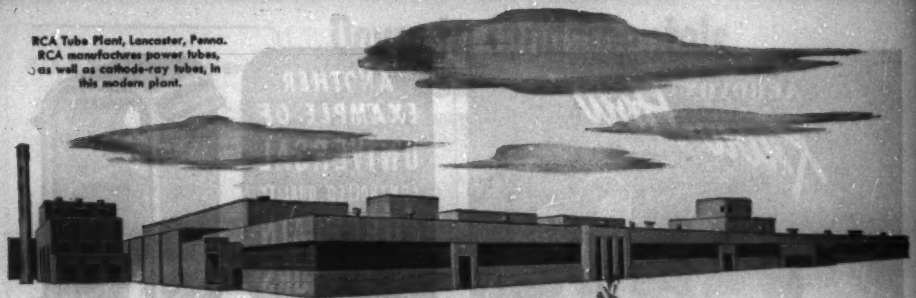


RCA Tube Plant, Lancaster, Penna. RCA manufactures power tubes, as well as cathode-ray tubes, in this modern plant.

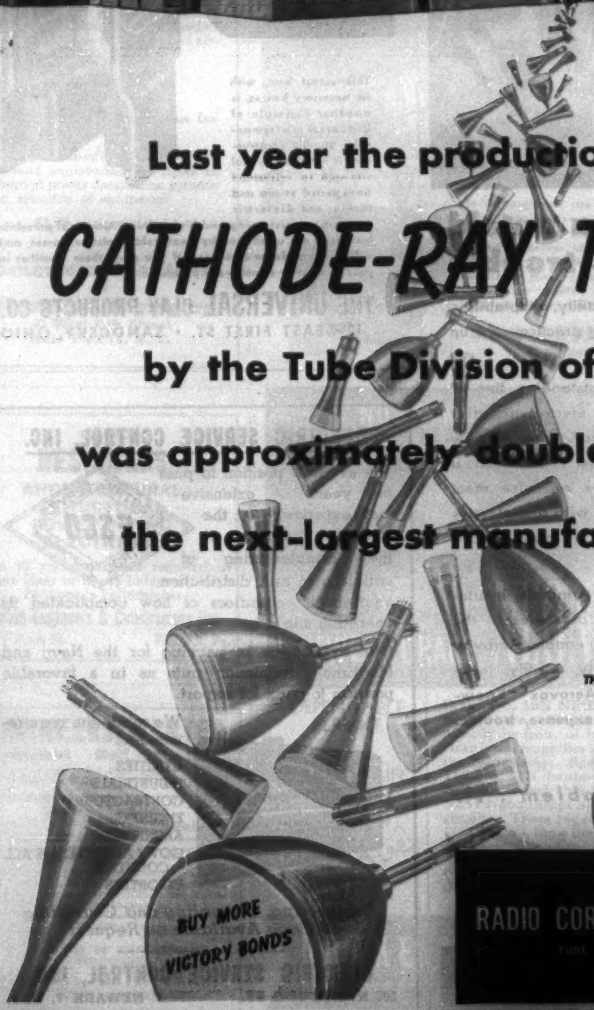
Last year the production of

CATHODE-RAY TUBES

by the Tube Division of RCA

was approximately double that of

the next-largest manufacturer



THE FOUNTAINHEAD OF MODERN TUBE DEVELOPMENT IS RCA

RCA

RADIO CORPORATION OF AMERICA

TUBE DIVISION · HARRISON, N. J.

. . . can save you untold time, expense, trouble

● Ingenuity, imagination, versatility, adaptability, coupled with sound engineering practice, add up to Aerovox "Know-How".

Of course Aerovox has an outstanding line of *standard* capacitors—paper, oil, electrolytic, mica and low-loss ultra-high-frequency types. A wide range of requirements are met with such a variety of listings. But Aerovox can also meet most of the extraordinary needs with *special* types that do not have to be billed at usual special prices. Here's why:

A tremendous variety of cans, terminals, insulators, mountings and production processes at the disposal of Aerovox engineers enable Aerovox to make up special types quickly, readily, inexpensively. So: Bear in mind Aerovox "Know-How"—and save untold time, expense, trouble.

● *Try us on that capacitance problem . . .*

AEROVOX Capacitors

INDIVIDUALLY TESTED

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This cutout box, with its necessary bosses, is another example of Universal craftsmanship. Sturdily constructed, it has the physical strength to withstand unexpected strain and stress; and dielectric strength to resist arcing and high voltage. Universal porcelain insulators are unaffected by heat, cold, moisture, fumes, and will not corrode or carbonize. If you need these qualities in your product—submit your problem.

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ELECTRIC SERVICE CONTROL ESCO Incorporated

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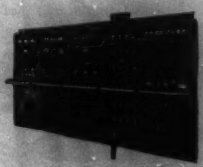

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Preferably those with EXPERIENCE ADAPTABLE TO AIRCRAFT

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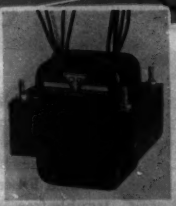
Or others with at least several years of engineering experience which will serve as a basis for aircraft work.

Permanent positions are available in the engineering of such planes as the Martin 202 transport, commercial version of the Martin MARS, and other new commercial and military commitments. Write including full information on education, experience and background,

to DIRECTOR OF ENGINEERING PERSONNEL
THE GLENN L. MARTIN COMPANY
BALTIMORE 3, MARYLAND

Down to fundamentals...
IN POST-WAR TRANSFORMER DESIGN



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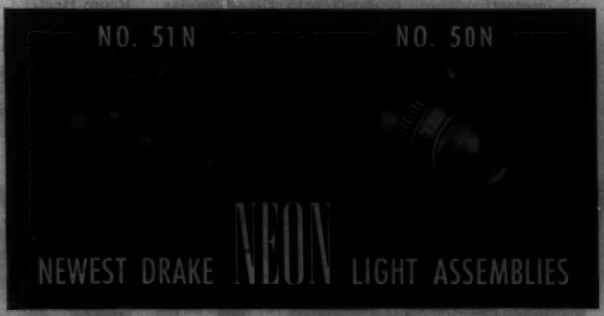

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GRAD ELEC ENGR; 34, married; 8 yrs exper des and devpmt of small elec-mech devices, presently employed Midwest, desires connection New York City or vicinity. Available December. E-154.

MECH-ELEC ENGR; young, married; M.S., Professional Engr. Six yrs supervising des devpmt and test of mech and elec devices. Desires pos with consulting firm or indus organization. E-155.

ELEC ENGR; 31, married; 5½ yrs util exper in overhead elec trans and distr planning, constr, maint; 3 yrs Naval Officer, serving as project engineer developing electronic devices. Desires sales engg pos or related work in Cal. Available Feb. 1, 1946. E-156-356-C-5-San Fran.

ELEC ENGR; Columbia; 35, married; supplementary courses in M.E., mathematics, aerodynamics. Exec and personnel management exper, 120 employees. Aircraft electronic and electrical equipment. Gas, electrical distr engg exper. Desires prod control. Location secondary. E-157.

ELEC ENGR; 28, single; grad degree H.V engrg; 4½ yrs exper high-frequency, high-voltage, high-vacuum as research engr; desires pos research and/or devpmt with mfg or consulting firm; prefer to locate Cal. E-158.

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SALES ENGINEERS, under 35, with sales experience, principally with electric light and power companies or old established companies. Basic engineering training desired. Apply by letter submitting complete history and salary expected. W-6224.

SAFETY ENGINEER, electrical graduate, 35–40, with considerable utility operating and safety engineering experience, to cover utility plants in New York State, Pennsylvania and New Jersey. Salary, $5000 a year. Headquarters, New York, N. Y. W-6228.

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ELECTRONIC ENGINEER for development of special circuits and electro-mechanical apparatus. Should be capable of designing transmitter circuits and some experience with piezo electric signalling devices desirable. Salary open. Location, Connecticut. W-6308.

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ELECTRONIC ENGINEER, electrical graduate or Physicist, with Ph.D. or D.Sc. degree, with five to ten years' design, research and development experience for application development program. Salary, $6000–$6500 a year. Location, New York, N. Y. W-6204(a).

ENGINEERS. (a) Research and Development Engineers with background of experience in electronics, preferably audio and circuit design. Must have good theoretical background but be heavy on application. Salary, $4500–$6000 a year. (b) Research and Development Assistants. Must have B.E. degrees; need not have any experience but knowledge of electronics and acoustical work desirable. Salary, $3600–$4200 a year. (c) Laboratory Engineer, preferably with some inventive talent, and ability to work with his hands, i.e., experience as a model maker, etc. Salary, $3600–$3500 a year. Location, New York Metropolitan Area. W-6200.

LIGHTING ENGINEER, 25–30, electrical graduate, to make surveys, draw up specifications, and make layouts for public utility company. Some application engineering covering industrial equipment and domestic appliances will also be involved. Salary, $3000–$3800 a year. Location, New York State. W-6311.

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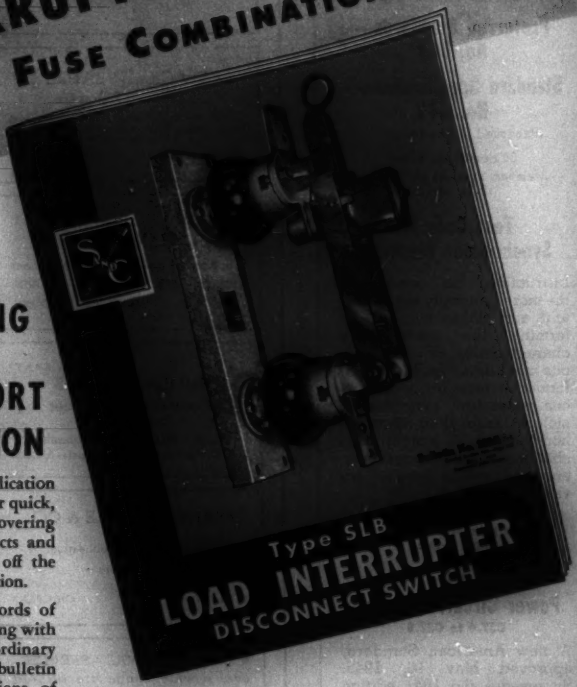

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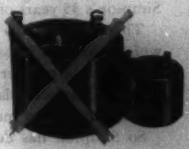

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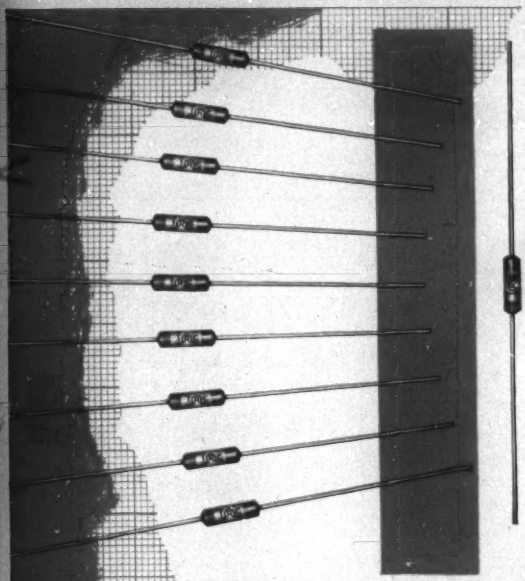

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